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UNIVERSITÉ DE MONTREAL

DIFFERENTIAL MICROWAVE DEVICE CHARACTERIZATION

WEI LIU
DÉPARTEMENT DE GÉNIE ÉLECTRIQUE
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présenté par : LIU Wei

En vue de l'obtention du diplôme de : Maîtrise ès sciences appliquées

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To my family

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RÉSUMÉ

Cette thèse présente une méthode systématique pour caractériser les dispositifs équilibrés en mode différentiel pur. Les techniques et les procédures développées dans ce projet sont générales et peuvent être appliquées à n'importe quel dispositif différentiel quelle que soit la fréquence.

Les transistors Va-et-Vient (Push-Pull) deviennent de plus en plus répandus mais sont très difficiles à caractériser car il n'y a aucun système qui puisse être employé pour mesurer ce type de dispositif en mode différentiel pur. Les quelques approches existantes utilisent toujours la mesure des paramètres S, ce qui devient inutile quand les dispositifs fonctionnent dans la région non-linéaire. Le but de cette thèse était de développer un système différentiel de traction de charge (Load-Pull), seul moyen de caractériser totalement les dispositifs Va-et-Vient en mode différentiel.

Cette étude comporte six parties. Tout d'abord une méthode systématique de calcul de paramètres S en mode mixte est présentée. Basés sur les Paramètres S en mode mixte, le coefficient de réflexion ainsi que les pertes des composants en mode différentiel peuvent être calculéS.

En second lieu, sont présentés les synthétiseurs d'impédances électro-mécaniques (Tuners) différentiels qui ont été créés durant ce projet. Les synthétiseurs d'impédances peuvent présenter un coefficient de réflexion variable en amplitude et phase pour chaque voie.

Troisièmement, un support de test différentiel a également été fabriqué pour relier un dispositif Va-et-Vient (Push-Pull) aux synthétiseurs d'impédances différentiels en entrée et en sortie. Le procédé de calibrage du support de test est également présenté.
Une nouvelle méthode pour caractériser le transformateur symétrique (balun), et l'implémenter dans le système est discutée suite à ça.

Pour finir le logiciel a été développé sur la base de cette nouvelle théorie de traction de charge différentielle.

ABSTRACT

This thesis describes a systematic method to characterize differential (push pull) devices fully in differential mode. The techniques and procedures developed in this project are general and can be applied to any differential device measurement at any frequency.

The non-linear differential circuit is getting more and more popular. But there are many difficulties of characterization since there is no genuine measurement system that can be used to measure this type of circuit in true differential mode. Some approaches still rely on S –parameter measurement, which is not useful when the devices are working in the non-linear region. It is the purpose of this thesis to develop differential load pull system, which is the real tool to characterize differential devices.

There are 6 major topics presented in this project. First a systematic calculation method of mixed mode S–parameters is presented based on literature. Using mixed mode S-parameters, the differential mode reflection coefficient factor and losses of the components can be computed.

Secondly, differential tuners are developed in this project, which can present variable reflection coefficients at each path of differential signal, both amplitude and phase of reflection coefficients at each path can be controlled.

Thirdly, a differential test fixture is also developed to connect a push-pull device and differential tuners (input and output). The full calibration procedure is also developed.

Next a new method to characterize balun, and implementation of balun in differential load pull system is developed.

Lastly the software is developed based on the new differential load pull theory.

CONDENSÉ EN FRANÇAIS

CARACTÉRISATION DES DISPOSITIFS MICRO-ONDES DIFFERENTIELS

L'objectif de ce projet est de développer un nouveau système de mesure pour la caractérisation non-linéaire des dispositifs équilibrés (différentiels). La technique utilisée pour caractériser les dispositifs près de la saturation est bien connue sous le nom de: "Load-Pull". Le principe de la Traction de Charge, ou "Load-Pull", consiste à mesurer directement tous les paramètres importants désirés. Ceci nous renseigne avec précision sur l'impédance optimale à présenter à la sortie du dispositif afin que tous les paramètres associés tel que Puissance de sortie, PAE, impédance d'entrée, paramètres d'alimentation, etc., soient conformes aux spécifications. Etant donné que tous ces paramètres peuvent être pris en considération, on peut même réaliser une recherche d'optimum très complexe où plusieurs paramètres peuvent être considérés simultanément.

Le système de mesure Load-Pull est commercialisé et disponible sur le marché. Par exemple, Focus Micro-ondes Inc fabrique –entre autres- des systèmes Load-Pull depuis plus de 15 ans. Pourtant, jusqu'à présent, un tel système est utilisé exclusivement pour la caractérisation des dispositifs non-équilibrés (une seule terminaison) et, à la connaissance de l'auteur, il est incapable de mesurer des dispositifs équilibrés .

Le système Load / Source Pull Différentiel a été développé et réalisé dans cette optique. Toute la procédure d'étalonnage et les méthodes de conversion des paramètres du mode non-équilibré (une seule terminaison) au mode différentiel sera présentée. Les Synthétiseurs d'Impédances Micro-ondes Différentiels, les Montures de Test Différentielles et l'interfaçage "Balun" ont été conçus et fabriqués. Des dispositifs du type transistor Push-Pull, modèle: FLL400IP-2, fournis par Fujitsu Semiconductor, ont été testés.

0.1 INTRODUCTION

Les dispositifs équilibrés opèrant en mode différentiel, deviennent de plus en plus répandus dans la conception des amplificateurs micro-ondes à cause de leurs avantages.

Les dispositifs Push-Pulls sont les seuls à pouvoir délivrer le double de puissance, comparé à un dispositif à une seule terminaison. En plus, ils offrent d'autres avantages tel que l'immunité au bruit, des impédances d'adaptation plus élevées, donc plus faciles à réaliser, une masse virtuelle ainsi que l'annulation des harmoniques paires.

La structure équilibrée est montrée dans le schéma 1.2. En fait, le dispositif équilibré inclus deux transistors identiques. Les signaux RF équilibrés, c'est à dire de même amplitude mais déphasés de 180 degrés, sont injectés dans le dispositif. Une fois le signal équilibré (différentiel) injecté dans le dispositif, un signal différentiel amplifié sera livré à la sortie. Dans le dispositif, deux transistors sont interconnectés via une masse virtuelle de telle sorte que seulement les signaux en mode différentiel pourront le traverser. S'ils partageaient une masse physique, le signal en mode commun lui aussi serait amplifié avec le même gain

L'obstacle majeur auquel faire face est le fait que la plupart des équipements de test soient conçus pour la mesure de dispositifs à une seule terminaison. L'infrastructure est-elle aussi non-équilibrée. Ceci inclut les standards d'étalonnage, les lignes de transmission, les connecteurs et même le standard-industriel de l'impédance de référence.

0.2 LES PARAMETRES S

Aux fréquences micro-ondes, il est très difficile de mesurer directement la tension et le courant et ainsi modéliser les dispositifs en utilisant les matrices d'impédances ou d'admittances.
Une représentation dépendant directement des mesures d'ondes incidentes, réfléchies et transmises est donnée par les Paramètres S. Par principe, elles sont simples, bien adaptées aux analyses et capables de fournir suffisamment de connaissances pour résoudre les problèmes de mesure ou de conception.

Le gain entre les deux ports d'un réseau peut être défini en utilisant les Paramètres S. Il y en a trois définitions principales : le Gain Transducique, le Gain en Puissance et le Gain Disponible. Le système Load-Pull utilise le Gain Transducique du réseau pour calculer les mesures dans le plan de référence du dispositif sous test(DUT).

Le Gain Transducique est le rapport entre la puissance livrée à la charge et la puissance disponible à la source. Ce gain dépend des impédances d'entrée et de sortie.

Le Gain en Puissance est le rapport entre la puissance délivrée par le DUT à la charge et la puissance délivrée à l'entrée du DUT. Ce gain est indépendant de l'impédance de la source.

Le Gain Disponible est le rapport entre la puissance disponible du réseau et la puissance disponible de la source. Ce gain dépend de l'impédance de la source mais pas de celle de la charge à la sortie du dispositif.

Dans le système Load-Pull différentiel, le Gain Disponible est utilisé pour calculer les pertes à l'entrée alors que le Gain de Puissance est utilisé pour calculer les pertes à la sortie du DUT.

Les Paramètres S d'un deux-ports ne peuvent pas être cascadés directement. Ils doivent d'abord être convertis en paramètres T ou en paramètres ABCD dont les matrices seront multipliées. Par conversion inverse, la matrice T résultant de la multiplication donnera les Paramètres S cascadés.

0.3 LES PARAMETRES S en MODE MIXTE

Les dispositifs différentiels sont uniques avec leurs signaux qui sont référencés non seulement à la masse commune mais également l'un à l'autre.

La référence des signaux l'un à l'autre s'appelle le "mode différentiel" alors que le cas des signaux référencés à une masse commune s'appelle le "mode commun".

La technique des Paramètres S en mode mixte consiste à déterminer la réponse qui correspond aux modes différentiels et communs à tous les ports du dispositif lorsque l'un d'entre eux est stimulé par un signal différentiel.

La stimulation du mode commun, quant à elle, consiste à différencier la réponse du mode différentiel de celle du mode commun.

Une matrice S à mode mixte peut être structurée d'une façon similaire à la matrice S d'une seule terminaison dans laquelle chaque colonne représente une condition de stimulation différente et chaque rangée représente une condition de réponse différente. Contrairement à l'exemple de la seule terminaison, la matrice des paramètres S en mode mixte considère non seulement le port mais aussi le mode du signal à chaque port. La matrice en mode mixte décrit parfaitement la performance linéaire d'un réseau deux-ports différentiel.

Bockelman et Eisenstadt [2] ont développés une méthode pour convertir les données d'une seule terminaison au mode mixte utilisant des algorithmes mathématiques. Ces algorithmes montrent une relation entre les ondes générées par un analyseur de réseau vectoriel standard et les ondes différentielles et communes associées qui sont modélisés par les Paramètres S en mode mixte.

L'existence d'une transformation entre les Paramètres S standards et en mode mixte suggère deux approches différentes pour la mesure des circuits différentiels.

L'une des approches consiste à utiliser un analyseur de réseau traditionnel. Ce dernier mesure les Paramètres S standards en stimulant chaque port du circuit différentiel individuellement. Ces derniers sont ensuite transformés en Paramètres S en mode mixte pour fin d'analyse.

Alternativement, les Paramètres S en mode mixte d'un circuit différentiel, peuvent être mesurés directement en stimulant chaque mode individuellement.

0.4 LA THÉORIE DU LOAD PULL

Les mesures Load et Source Pull sont des mesures dépendantes des impédances. Ceci veut dire que le paramètre principal indépendant de la mesure n'est pas la fréquence, la puissance, la température, les vibrations ou la pression mais l'impédance d'entrée ou de sortie (représentées par leurs coefficients de réflexion), à la fréquence fondamentale ou harmonique, présentée au dispositif sous test (DUT).

Ces impédances sont normalement générées par un synthétiseur d'impédances (tuner). Le tuner est un composant passif qui fait varier l'impédance présentée au DUT pour une fréquence spécifique en fonction de la position mécanique des éléments intérieurs.
Cette méthode s'appelle le *Load Pull Passif*. Par ailleurs, il existe également une méthode pour générer les impédances d'une façon virtuelle c'est à dire en réinjectant à la sortie du dispositif le signal, après lui avoir fait subir un changement d'amplitude et de phase à l'aide de circuits actifs (circuits avec gain). Cette méthode a été proposée au milieu des années 70 et est généralement nommée *Load Pull Actif*.

Le système Load-Pull différentiel montré dans la figure 4.3, est un système de mesure dans lequel l'impédance de charge différentielle totale à la sortie (ou à l'entrée) est modifiée au moyen d'un synthétiseur d'impédance différentiel. Le signal d'entrée non-équilibré est divisé en deux signaux équilibrés par le balun d'entrée qui sont injectés dans le dispositif Push-Pull à travers le synthétiseur différentiel et le bloc d'entrée de la monture de test différentielle. Les signaux amplifiés par le DUT passent par le synthétiseur différentiel de la sortie et seront transformés en signaux non-équilibrés grâce au balun de sortie. Le signal non équilibré sera mesuré directement par un puissance–mètre, un analyseur de spectre ou n'importe quel instrument capable de mesurer la puissance micro-onde.

0.5 SIMULATION DU SYSTÈME

Dans le chapitre 5, des simulations ont été effectuées grâce au simulateur ADS de Agilent. Le but de cette simulation est de déterminer l'impédance différentielle de référence, de vérifier la transformation du mode mixte des paramètres S ainsi que d'étudier le principe des mesures Load-Pull dans la caractérisation des dispositifs différentiels.

Le balun micro-ondes est utilisé en simulation comme un objet. Il est simulé en tant que dispositif trois-ports sous conditions non-équilibré ainsi qu'un dispositif deux-ports en mode différentiel. La simulation montre l'impédance du système Load-Pull différentiel égale à une valeur de 100 Ohm. Celle-ci sera adoptée tout le long du développement du système.
Le Load-Pull d'un dispositif à une seule terminaison de même que le Load-Pull différentiel d'un dispositif Push-Pull sont exécutes avec ADS de Agilent. Les simulations révèlent que le concept du Load-Pull différentiel est faisable.

0.6 CONCEPTION DES SYNTHETISEURS MICRO-ONDES D'IMPEDANCES ET DE LA MONTURE DIFFÉRENTIELLE

Les Synthétiseurs Micro-ondes Différentiels (SMD) et la Monture de Test. Différentielle Micro-ondes (MTDM) sont conçus pour caractériser les transistors micro-ondes différentiels. Le SMD est un instrument électro-mécanique qui permet de positionner avec précision une sonde dans une ligne de transmission à fente ce qui génére avec précision des coefficients de réflexion élevés.

Le positionnement de la sonde est réalisé à l'aide d'un moteur pas à pas contrôlé par ordinateur ainsi que d'une vis verticale et d'un mécanisme horizontal relié par une courroie.

Les SMD sont basés sur deux lignes à fente coaxiales parallèles et sur 4 moteurs pas à pas. :es deux sondes bougent horizontalement et verticalement long de ces lignes. En bougeant la sonde, les impédances présentées aux deux ports de chaque ligne changent et par conséquent l'impédance différentielle totale vue par le dispositif sous test (DUT) peut être synthétisée. L'impédance totale peut être calculée avec beaucoup de précision en utilisant les Paramètres S en mode mixte.

Étant données les deux lignes à fentes du SMD pour présenter le coefficient de réflexion aux deux signaux différentiels, il est essentiel d'étudier l'effet de non-équilibre créé par cette structure. L'étude montre que la phase en transmission doit être équilibrée. Pour réaliser cela, une des deux lignes est conçue de sorte à être ajustable pour réaliser l'équilibre de la phase entre les deux chemins.

La Monture de Test Différentiel Micro-ondes (MTDM) est conçue pour supporter le dispositif sous test ainsi que le circuit d'alimentation. Le

dispositif Push-Pull a deux ports d'entrée et deux ports de sortie. Ainsi, deux lignes de transmission de 50 Ohm sont utilisées sur le substrat.
Afin d'éliminer ou de réduire les oscillations du DUT, le circuit d'alimentation est également implémenté sur le circuit imprimé de la monture.

0.7 BALUNS MICRO-ONDES

D'après la définition classique d'un point de vue port non-équilibré, les baluns sont en fait des dispositifs trois-ports avec une impédance de 50 Ohm à un port et 25 Ohm aux deux autres ports. Les baluns jouent un rôle très important dans les mesures différentielles.

Il était très important de trouver une méthode pour caractériser le balun et l'intégrer dans le banc de mesure. Les baluns sont utilisés à l'entrée (resp. à la sortie) pour diviser (resp. combiner) la puissance. L'impédance 25-Ohm est ramenée à 50 Ohm à l'aide d'un transformateur multi-section afin que le coefficient de réflexion des synthétiseurs puisse couvrir tout l'abaque de Smith.

Le mode mixte des paramètres S est utilisé pour caractériser les baluns. Le balun est ensuite traité comme un dispositif deux-ports en se servant uniquement des paramètres Sss11, Sds21, Ssd12 et Sdd22.
Lors des mesures, la puissance disponible est mesurée et grâce au Paramétres S du balun, la puissance en entrée du DUT peut-être calculée.
Enfin, les pertes de puissance sont calculées et utilisées pour déterminer la puissance de sortie du DUT.

0.8 SYSTÈME d'ÉTALONNAGE

Tout les composants utilisés dans le banc de mesure doivent être étalonnés (calibrés) avec précision. Dans ce projet, les Paramètres S et les Paramètres S en mode mixte sont adoptés pour étalonner le banc de mesure et un analyseur de réseau est utilisé pour mesurer les Paramètres S de tous les composants incluant les Synthétiseurs Différentiels SMD.
Les fichiers de Paramètres S mesurés sont chargés dans l'ordinateur. Le logiciel lit et interprète ces fichiers, les convertit en Paramètres S en mode mixte et calcule le coefficient de réflexion et les pertes durant les mesures.

Pour mesurer et caractériser la Monture de Test Différentielle MTDM, la technique d'étalonnage Through-Reflect-Line, ou TRL, est utilisée pour extraire les fichiers de Paramètres S de chaque moitié. La technique d'étalonnage TRL utilise la connection directe (through), la ligne à retard (delay) et un standard de réflexion (court circuit ou circuit ouvert). Pour chacun de ces standards, les Paramètres S sont mesurés. D'après ces données, le programme calcule les Paramètres S des composants à l'entrée et à la sortie du banc de mesure. Par suite, les paramètres S en mode mixte sont extraits.

0.9 ANALYSE ET MESURE DES DONNEES

Le dispositif push-pull; FLL400IP-2, courtoisie de Fujitsu Semiconductor, a été testé avec le système Load-Pull différentiel. Les contours de Load-Pull mesurés, montrent sont très proches des données et spécifications publiées ainsi que de celles obtenues en mesurant les Paramètres S faible signal.

0.10 CONCLUSION

Ce projet présente une méthode systématique pour la caractérisation des dispositifs équilibrés en micro-ondes. Un système Load-Pull Différentiel a été conçu et développé. La théorie d'un tel système, les Synthétiseurs Différentiels SMD, la procédure innovatrice d'étalonnage du système, l'introduction des Paramètres S en mode mixte et finalement, la nouvelle méthode d'encastrement des Paramètres S de la monture de test sont les principales contributions apportées par ce projet.

En se basant sur les résultats et l'expérience acquis au cours de cette thèse, certaines recommandations peuvent être faites comme suit :

1) Le coefficient de réflexion présenté au plan de référence du DUT n'est pas assez élevé à cause des pertes de la monture de test différentielle. La solution serait d'ajouter une sonde de pré-adaptation (pre-matching) devant le SMD.
2) Il y a un besoin de contrôle des impédances harmoniques. A cause de la faible bande passante du balun, l'avantage de l'annulation des harmoniques paires n'a pas pu être mis en valeur dans ce projet. Néanmoins, durant la mesure du dispositif, de forts signaux harmoniques ont été détectés par l'analyseur de spectre. Le fait d'avoir la capacité de synthétiser les impédances harmoniques donnerait une information additionnelle utile pour la conception d'un amplificateur.
3) Les baluns micro-ondes sont un élément essentiel dans les systèmes différentiels. Malheureusement, la structure deux-ports du balun a une isolation de seulement –6dB ce qui pourrait causer l'instabilité du

dispositif. En fait, le coupleur hybride de 180-degrés - 3 dB, pourrait être utilisé pour diviser le signal d'entrée et combiner les signaux à la sortie. Dans ce cas, le transformateur conçu pour adapter le balun au SMD devient par là même inutile. De plus, le coupleur 180-degrès a une meilleure isolation que celle de l'isolateur. Par contre, ce coupleur coaxial, disponible sur le marché, n'offre pas un bon équilibre d'amplitude et de phase. Le coupleur demande une charge additionnelle de 50-ohm pour un seul port isolé ce qui s'avèrerait difficile à effectuer et entraînerait une élévation du coût.

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LIST OF SYMBOLS AND NOTATIONS

DMT	Differential Microwave Tuner
DTF	Differential Test Fixture
DLPS	Differential Load Pull System
PHT	Programmable Harmonic Tuner
PMT	Pre-matching Tuner

CHAPTER 1
INTRODUCTION

Microwave communication systems, as well as all other RF applications, require optimum amplifier design to achieve maximum output power, power added efficiency (PAE) and other targets. These parameters significantly influence the commercial success of today's microwave applications.

Typically the optimum load impedance and all the other related parameters have been determined from a given model for the active device (MSFET, BJT, HBT, HEMT, etc). However, all these models have been extracted from small signal measurement and DC curves. In order to meet today's requirements transistors need to operate near saturation. In this region most models become inaccurate.

The easiest way to overcome these problems is the direct measurement of these desired parameters. Such measurements produce the accurate knowledge of optimum load impedance and the associated parameters such as output power, PAE, input impedance, bias parameters, etc. Since all parameters can be taken into account, even a complex optimum goal for the operation that considers more than one parameter can be achieved.

Load pull and source pull techniques [8], [10], are the best ways to measure the optimum impedance on both the input and output of the devices.

1.1 BALANCED CIRCUIT

The balanced devices [6], [7], [13], [20], [31], that are working in differential mode become more and more popular in designing microwave amplifiers due to the following advantages:

1. Noise sources such as those from power supplies, adjacent circuitry, and other external sources are coupled either electrically or electro-magnetically. These noise sources tend to couple in the common-mode, and therefore cancel in differential mode.

2. Even Harmonic components are cancelled [16]. Differential signals are anti-phase at the fundamental frequency, and in-phase at the even harmonics.

3. Virtual ground in a differential circuit is independent of the physical ground. Therefore, differential devices can tolerate poor RF grounds better than unbalanced devices.

4. Differential impedance is higher (Zin Gate-to-Gate and Zout Drain-to-Drain) than single-ended device impedances with the same output power. Thus it makes design of matching easier.

5. Virtual ground makes a large physical ground unnecessary. This makes an amplifier structure more compact.

Furthermore, single RF power transistor seldom satisfies today's design criteria. Several devices in separate packages, or in the same package (balanced, push-pull or dual transistors), must be coupled to obtain the required amplifier output power. Since high power transistors have very low impedance, designers are challenged to match combined devices to a load. This often leads to the choice of a push-pull technique because it allows the input and output transistor impedances to be connected in series for RF operation.

1.2 BALANCED CIRCUIT STRUCTURE

A diagram shown in figure 1.1 is a single-ended structure. Indeed only one transistor is involved. An unbalanced signal is injected at the input and an unbalanced signal is delivered at the output.

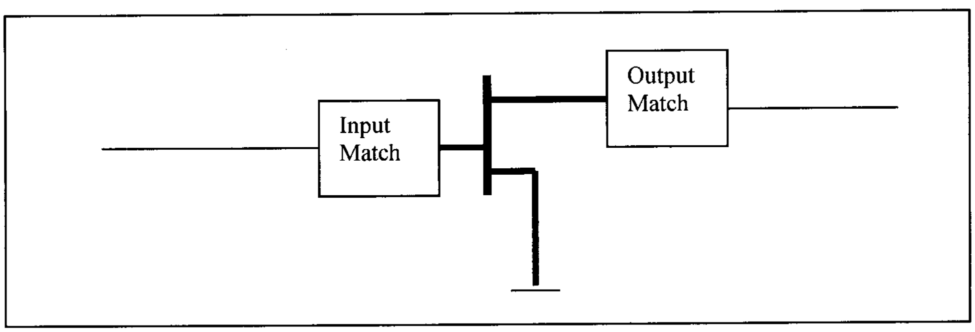

Figure 1.1 Unbalanced Device Structure

A balanced device (figure 1.2) actually includes two identical transistors. The differential (anti-phase and equal amplitude) RF signal is injected into the device. Once the device is driven by a balanced (in this case differential) signal it will deliver the differential signal at the output accordingly. Two transistors are connected by virtual ground so that only differential mode signals are allowed to pass. On the other hand if the virtual ground is shared with physical ground then common mode signals can also pass, producing the same gain.

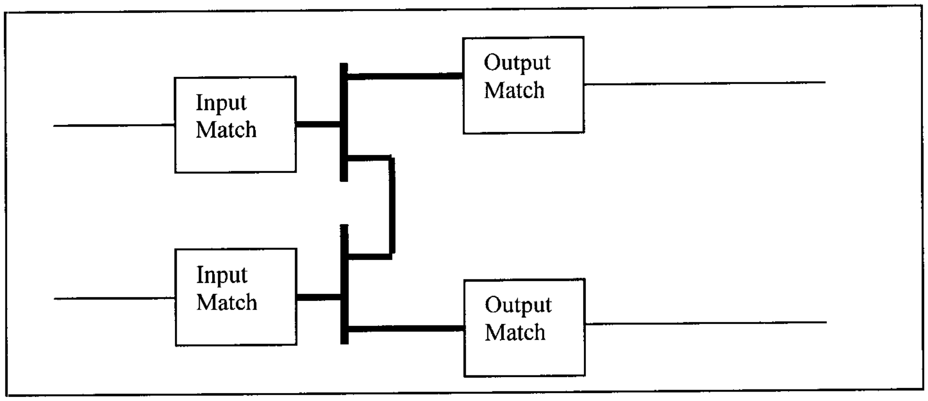

Figure 1.2 balanced Device Structure

1.3 CHARACTERIZATION DIFFICULTIES

A major stumbling block is that most test equipments are intended for single-ended devices. The related infrastructure is also unbalanced. This includes things that are often taken for granted, such as calibration standards, transmission lines and connectors, and even industry-standard reference impedance.

When devices are working in non-linear regions, there is no genuine and effective measurement system to characterize these devices in differential mode, so far.

For balanced devices (push-pull) without internal coupled circuit, some designers treat half transistor as a single-ended device individually [25]. The optimum impedance of half device is assumed as half of the differential impedance.

Though it is well known differential circuits work best when driven by differential inputs. The single-ended response of a circuit designed for differential operation can show large artifacts because parasitic components intended to remain at common mode come into play. Spurious peaks may appear in the frequency response. While the input and output impedance match may not be valid.

1.4 OBJECTIVES

This project develops a measurement system to characterize balanced (differential) devices in true differential mode.

The concept involves the use of microwave tuners to match devices at both the input and output sides. The measurement will then be done at different matching conditions by using the proper instruments. The desired design targets can be reached at one of many load or source impedances that are desirable to be used in power amplifier design, as well as other RF applications.

The Differential Microwave Tuner (DMT) is developed in this project as well as other differential components such as differential test fixtures, and balun transition boards.

1.5 ORGANIZATION

This thesis includes 11 chapters. Chapter 1 describes the motivation and objective of this research work. Followed by chapter 2, in which scattering parameters are reviewed. Scattering parameters are very important for this project since they are used to calibrate two-port components in the system.

Furthermore, mixed mode S-parameters are used to calibrate four and three ports components in differential mode. These mixed mode S-parameters are introduced in chapter 3.

Load pull technique of unbalanced devices is introduced in chapter 4. The differential load pull technique is developed based on the single ended load pull technique. Simulations are presented in chapter 5. Agilent ADS simulator is used to simulate differential impedance, and transformation of mixed mode S-parameters. Simulations of a single-ended load pull system and differential load pull systems are also performed. Based on the results, the concept of a differential load pull system is developed.

In chapter 6, the theory and design of differential microwave tuners as well as differential test fixture are discussed in detail. Baluns play very important role in the differential measurement of a system, and is addressed in detail in chapter 7.

System calibration is another challenge. Device measurements are done after the system is carefully calibrated. Calibration procedure is presented in chapter 9. Lastly, experiments and measurement results are shown in chapter 10. Software development is one of the big parts in this project. Software is addressed as a part of chapter 10.

1.6 MAJOR CONTRIBUTIONS

There are 4 major contributions in this project:

1. A new theory of differential load pull system is presented.

2. Mixed mode S-parameters are adopted to calibrate differential load pull system.

3. Differential microwave tuners and differential test fixture are developed.

4. A general method of de-embedding differential parameters is developed.

CHAPTER 2
SCATTERING PARAMETERS

At microwave frequencies it is very difficult to measure voltage and current directly by using impedance or admittance matrices. A representation in accordance with direct measurement with incident, reflected, and transmitted waves, is given by the scattering parameters [9].

Linear networks, or nonlinear networks operating with signals sufficiently small to cause the networks to respond in a linear manner, can be completely characterized by parameters measured at the network terminals without regard to the contents of the networks. Once the parameters of a network have been determined, its behavior in any external environment can be predicted, again without regard to the contents of the network.

S-parameters are important in microwave design since they are easier to measure and work with at high frequencies than other kinds of parameters. They are conceptually simple, analytically convenient, and capable of providing a great insight into a measurement or design problem.

2.1 INTRODUCTION

A set of parameters can be used to describe the scattering and reflection of traveling waves when a network is inserted into a transmission line. S-parameters are normally used to characterize high frequency networks, where simple models, valid at lower frequencies, cannot be applied. S-parameters are normally measured as a function of frequency, so when looking at the formulae for S-parameters it is important to note that frequency is implied, and that the complex gain (i.e. gain and phase) is also assumed. For this reason, S-parameters are often called complex scattering parameters.

When the incident wave travels through the network, its value is multiplied (i.e. gain and phase are changed) by the scattering parameter (which is analogous to the gain of the network), thus giving the resulting output value. For example, when the wave travels through a network, the output value of the network is simply the value of the wave multiplied by the relevant S-parameter.

The definition of S-parameters is shown in (2.1), (2.2) and (2.3).

$$\begin{bmatrix} V_1^- \\ V_2^- \\ \cdot \\ \cdot \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \cdot & \cdot & S_{1N} \\ S_{21} & S_{22} & \cdot & \cdot & S_{2N} \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ S_{N1} & S_{N2} & \cdot & \cdot & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ \\ \\ V_N^+ \end{bmatrix} \tag{2.1}$$

V_n^+ is the amplitude of voltage wave incident on port n, and V_n^- is the amplitude of wave reflected from the port n. The scattering parameters matrix is defined in relation to these incident and reflected waves as

$$[V^-] = [S][V^+] \tag{2.2}$$

So, the “reflected” or output wave from each port is a function of the input wave at every port. A specific element of the [S] matrix can be defined as

$$S_{ij} = \left.\frac{V_i^{-}}{V_j^{+}}\right|_{V_k^{+}=0\ for k \neq j} \tag{2.3}$$

Where Sij is found by driving port j with an incident wave of voltage V_j^{+}, and the measuring reflected wave amplitude V_i^{-} , coming out of port I, The incident waves on all ports except j[th] port are set to zero. It means all ports should be terminated in matched loads to avoid reflections.

2.2 S-PARAMETERS DERIVATION

K. Kurokawa [1] defined generalized scattering parameters. These parameters describe the interrelationships of a new set of variables (a_i, b_i). The variables a_i and b_i are normalized complex voltage waves incident on and reflected from the i[th] port of the network. They are defined in terms of the terminal voltage Vi, the terminal current Ii, and arbitrary reference impedance Zi, where the asterisk denotes the complex conjugate:

$$a_i = \frac{V_i + Z_i I_i}{2\sqrt{|\operatorname{Re}(Z_i)|}} \tag{2.3}$$

$$b_i = \frac{V_i - Z_i^{*} I_i}{2\sqrt{|\operatorname{Re}(Z_i)|}} \tag{2.4}$$

The independent variables a_1 and a_2 are normalized incident voltages, as follows:

$$a_1 = \frac{V_1 + Z_0 I_1}{2\sqrt{|\operatorname{Re}(Z_0)|}} = \frac{voltage\,wave\,incident\ on\ port1}{\sqrt{Z_0}} = \frac{V_{i1}}{\sqrt{Z_0}} \tag{2.5}$$

$$a_2 = \frac{V_2 + Z_0 I_2}{2\sqrt{|\operatorname{Re}(Z_0)|}} = \frac{voltage\ wave\ incident\ on\ port2}{\sqrt{Z_0}} = \frac{V_{i2}}{\sqrt{Z_0}} \tag{2.6}$$

Dependent variables b1, and b2, are normalized reflected voltages:

$$b_1 = \frac{V_1 - Z_0 I_1}{2\sqrt{|\mathrm{Re}(Z_0)|}} = \frac{\textit{voltage wave reflected from port1}}{\sqrt{Z_0}} = \frac{V_{r1}}{\sqrt{Z_0}} \tag{2.7}$$

$$b_2 = \frac{V_2 - Z_0 I_2}{2\sqrt{|\mathrm{Re}(Z_0)|}} = \frac{\textit{voltage wave reflected from port2}}{\sqrt{Z_0}} = \frac{V_{r2}}{\sqrt{Z_0}} \tag{2.8}$$

The linear equations describing the two-port network are then:

$$b_1 = s_{11} a_1 + s_{12} a_2 \tag{2.9}$$

$$b_2 = s_{21} a_1 + s_{22} a_2 \tag{2.10}$$

$$s_{11} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0} \tag{2.11}$$

S_{11} is the input reflection coefficient with the output port terminated by a matched load.

$$s_{22} = \left.\frac{b_2}{a_2}\right|_{a_1 = 0} \tag{2.12}$$

S_{22} is the output reflection coefficient with the input port terminated by a matched load.

$$s_{21} = \left.\frac{b_2}{a_1}\right|_{a_2 = 0} \tag{2.13}$$

S_{21} is the forward transmission (insertion) gain with output port terminated in a matched load.

$$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0} \tag{2.14}$$

S_{12} is the reserve transmission (Insertion) gain with the input port terminated in a matched load.

Notice that:

$$S_{11} = \frac{b_1}{a_1} = \frac{\frac{V_1}{I_1} - Z_0}{\frac{V_1}{I_1} + Z_0} = \frac{Z_1 - Z_0}{Z_1 + Z_0} \tag{2.15}$$

$$Z_1 = Z_0 \frac{1 + S_{11}}{1 - S_{11}} \tag{2.16}$$

Z_1 is the impedance at port 1.

This relationship between reflection coefficient and impedance is the basis of the Smith Chart calculator. Consequently, the reflection coefficients s11 and s22 can be plotted on Smith Charts, converted directly to impedance, and easily manipulated to determine matching networks for optimizing a circuit design.

Another advantage of S-parameters is the simple relationship between the variables a_1, a_2, b_1, and b_2, and various power waves:

$|a_1|^2$ is

Power incident on the input port of the network

Power reflected from source

$|b_1|^2$ is

Power reflected from the input port of the network

Power available from a source minus the power delivered to the input of the network.

$|a_2|^2$ is

Power incident on the output of the network

Power reflected from the load

$|b_2|^2$ is

Power reflected from the output port of the network

Power incident on the load

Power that would be delivered to a Z load if it is matched

S-parameters are simply related to power gain and mismatch loss, quantities are of more interest than the corresponding voltage functions:

$$|S_{11}|^2 = \frac{\text{Power reflected from the network input}}{\text{Power incident on the network input}} \tag{2.17}$$

$$|S_{22}|^2 = \frac{\text{Power reflected from the network output}}{\text{Power incident on the network output}} \tag{2.18}$$

$$|S_{21}|^2 = \frac{\text{Power delivered to the Zo load}}{\text{Power available from Zo source}} \tag{2.19}$$

$$|s_{12}|^2 = \frac{Power\ delivered\ to\ the\ Zo\ source}{Power\ available\ from\ Zo\ load} \tag{2.20}$$

2.3 GAIN OF THE NETWORK

It is essential to review the relationship between S-parameters and gain of the network. Network gain is the main parameter needed in a Differential Load Pull System to de-embed the measurement of raw data to the DUT plane.

The typical two-port network is shown below in figure 2.1.

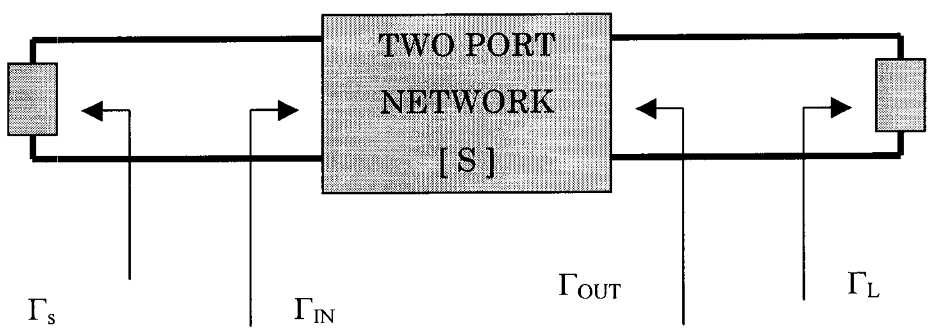

Figure 2.1 Two-Port Network

Where

$$\Gamma_{OUT} = s_{22} + \frac{s_{21}s_{12}\Gamma_s}{1 - s_{11}\Gamma_s} \tag{2.21}$$

$$\Gamma_{IN} = s_{11} + \frac{s_{21}s_{12}\Gamma_L}{1 - s_{22}\Gamma_L} \tag{2.22}$$

The above equations represent the true input or output reflection coefficients of the two-port network, having any arbitrary terminations.

In general, there are three major gain definitions, namely Transducer Gain, Power Gain and Available Gain. They are widely used in this project.

2.3.1 TRANSDUCER GAIN

Transducer Gain is the ratio of power delivered to the load to the power available from the source. This gain depends both on source and load impedances.

$$G_T = \frac{P_{del}}{P_{avs}} = \frac{1-|\Gamma_s|^2}{|1-\Gamma_{IN}\Gamma_s|^2}|s_{21}|^2\frac{1-|\Gamma_L|^2}{|1-s_{22}\Gamma_L|^2} \tag{2.23}$$

or

$$G_T = \frac{P_{del}}{P_{avs}} = \frac{1-|\Gamma_s|^2}{|1-s_{11}\Gamma_s|^2}|s_{21}|^2\frac{1-|\Gamma_L|^2}{|1-\Gamma_{OUT}\Gamma_L|^2} \tag{2.24}$$

2.3.2 POWER GAIN

Power Gain is the ratio of power delivered into the load to the power delivered to the input of the two-port network. This gain is independent of source impedance. In a Differential Load Pull System, the power gain is used to compute power loss of the output section.

$$G_p = \frac{P_{del-out}}{P_{del-in}} = \frac{1}{|1-\Gamma_{IN}|^2} |s_{21}|^2 \frac{1-|\Gamma_L|^2}{|1-s_{22}\Gamma_L|^2} \tag{2.25}$$

2.3.3 AVAILABLE GAIN

Available Gain is the ratio of the power available from the network to the power available from the source. This gain depends on source impedance but load impedance. In Differential Load Pull System, the available gain is used to compute loss of the input section.

$$G_{av} = \frac{P_{av-network}}{P_{av-source}} = \frac{1-|\Gamma_s|^2}{|1-s_{11}\Gamma_s|^2} |s_{21}|^2 \frac{1}{|1-\Gamma_{OUT}|^2} \tag{2.26}$$

2.4 TWO PORT S-PARAMETER CASCADE

Let us now proceed with discussing a set of network parameters used when cascading networks. Two-port S-parameters cannot be cascaded directly. One solution is to convert them to T-parameters or ABCD parameters for multiplication, then cascaded S-parameters can be obtained from converting T or ABCD parameters back to S-parameters format.

2.4.1 T-PARAMETERS

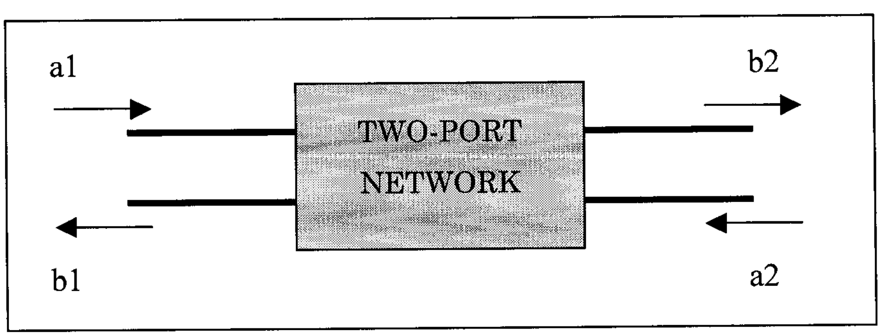

Figure 2.2 Two-Port Networks S-Parameters Definition

The definition of the two port S-parameters is the following:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{2.27}$$

The definition of the two port T-parameters is the following.

$$\begin{bmatrix} b_1 \\ a_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} a_2 \\ b_2 \end{bmatrix} \tag{2.28}$$

Manipulating the S-parameters equations into the appropriate form results in obtaining the T-parameters. Notice that the denominator of each of these terms is S21. We can also find the S-parameters as a function of the T-parameters.

The transformation between S-parameters and T-parameters can be found as the following:

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \dfrac{s_{12}s_{21} - s_{11}s_{22}}{s_{21}} & \dfrac{s_{11}}{s_{21}} \\ \dfrac{-s_{22}}{s_{21}} & \dfrac{1}{s_{21}} \end{bmatrix} \tag{2.29}$$

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \dfrac{T_{12}}{T_{22}} & \dfrac{T_{11}T_{22} - T_{12}T_{21}}{T_{22}} \\ \dfrac{1}{T_{22}} & \dfrac{-T_{21}}{T_{22}} \end{bmatrix} \tag{2.30}$$

While we defined the T-parameters in a particular way, we could have defined them such that the output waves are the dependent variables and the input waves are the independent variables. This alternate definition can result in some situations when designing with active unilateral devices.

Using the alternative definition for the transfer parameters, the denominator in each of these terms is S12 rather than S21 as we saw earlier. Working with very networks or amplifiers, S12 is very small number, which will cause calculation inaccuracy.

Since the output waves of the first network are identical to the input waves of the second network, using T-parameters for the two networks, we can simply multiply the two T-parameter matrices and arrive at a set of equations for the overall network.

Since matrix multiplication is, in general, not commutative, these T-parameter matrices must be multiplied in the proper order. When cascading networks, it is necessary to multiply the matrices in the same order as the networks are connected. Using the alternate definition for T-parameters previously described, this matrix multiplication must be performed in reverse order.

This transfer parameter set becomes very useful when using computer-aided design techniques where matrix multiplication is an easy task.

2.4.2 ABCD PARAMETERS

S-parameters can alternatively be cascaded by converting them into ABCD parameters [23]. The ABCD matrix is defined for a two-port network in terms of the total voltages and currents as shown in the figure 2.4 and the following:

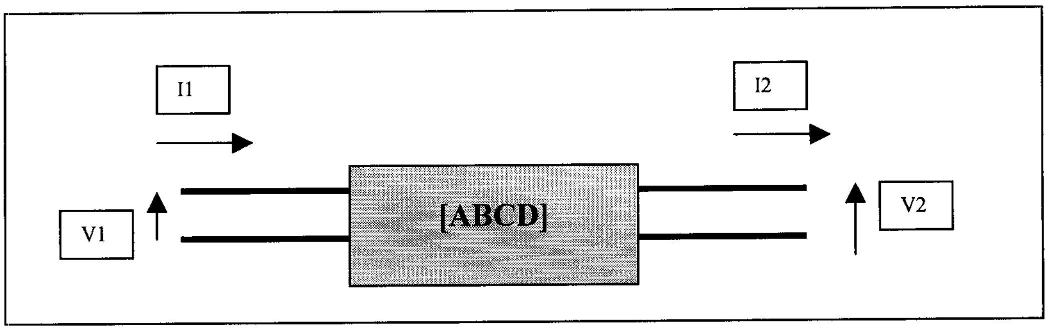

Figure 2.4 Two-Port ABCD Parameters

The definition of the ABCD parameters is the following:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{2.31}$$

The relationship between S-parameters and ABCD parameters is the following:

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \dfrac{A + B/Z - CZ - D}{A + B/Z + CZ + D} & \dfrac{2(AD - BC)}{A + B/Z + CZ + D} \\ \dfrac{2}{A + B/Z + CZ + D} & \dfrac{-A + B/Z - CZ - D}{A + B/Z + CZ + D} \end{bmatrix} \tag{2.32}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \dfrac{(1+S_{11})(1-S_{22}) + S_{21}S_{12}}{2S_{21}} & \dfrac{(1+S_{11})(1+S_{22}) - S_{21}S_{12}}{2S_{21}} Z_0 \\ \dfrac{(1+S_{11})(1+S_{22}) - S_{21}S_{12}}{2S_{21}} \dfrac{1}{Z_0} & \dfrac{(1-S_{11})(1+S_{22}) + S_{21}S_{12}}{2S_{21}} \end{bmatrix} \tag{2.33}$$

2.5 MULTIPORT PARAMETERS CASCADE

In this project, three port parameters are needed due to the use of microwave baluns, which are three port devices. The Y matrix, Z matrix, and S matrix are very useful to calculate multi-port networks. The details are not presented in this paper, but can be found in any microwave basics article.

The relationship [33] between a Y matrix and a S matrix is the focus of this section, since they are the basis of the software computing routine.

$$[S]=[E+Y]^{-1}[E-Y]=2[Y+E]^{-1}-[E] \tag{2.34}$$

$$[Y]=[E+S]^{-1}[E-S]=2[S+E]^{-1}-[E] \tag{2.35}$$

Where E is the unit matrix and Y is the normalized admittance matrix.

2.6 CONCLUSION

S-parameters provide a very convenient tool for high frequency linear device characterization. The defined T and ABCD parameters allow the S-parameters to be cascaded very easily by implementing the transformation in a computer program.

The transformation between Multi-port S-parameters and Y parameters is used to characterize three port linear devices in this project.

CHAPTER 3
MIXED MODE S-PARAMETERS

When S-parameters for single-ended networks are understood, one can extend this knowledge of S-parameters to characterize differential circuits. A differential circuit will be studied in order to arrive at an understanding of differential S-parameters.

3.1 INTRODUCTION

Differential components are unique in that signals are referenced not only to a common ground but to each other as well [24]. Signals referenced to each other are called "differential mode" and the signals referenced to a common ground are called "common mode" signals.

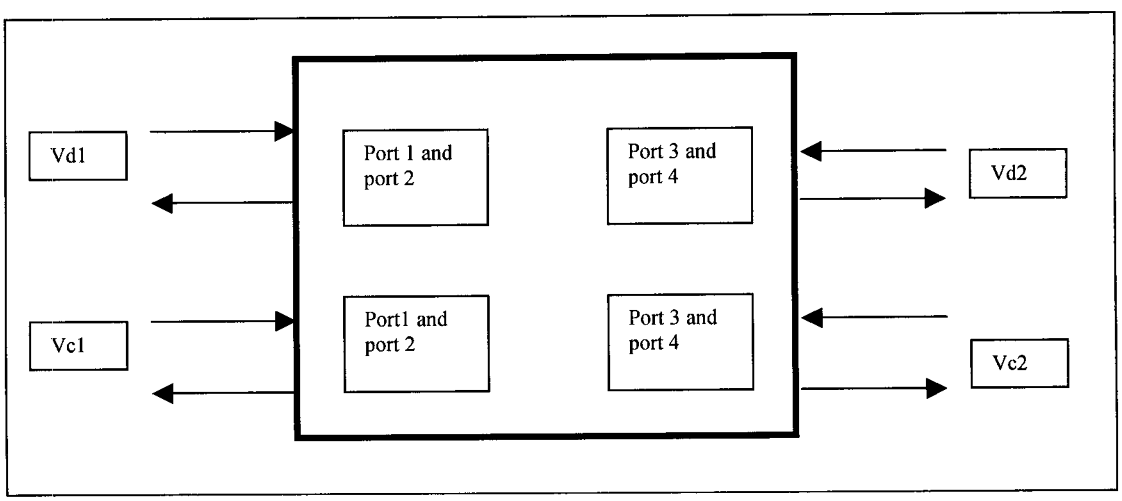

Figure 3.1 Linear Two-Port Differential Network

Common-mode signals are induced at the terminals of the device with the same phase and amplitude relationship. While a differential component has no performance advantage over a single-ended component when used in common mode, it exhibits significant benefits when used in differential mode because it will transmit differential mode signals and reject common-mode signals. For example, noise from a power supply will affect both terminals of the device equally with the same phase relationship. The device does not respond to these common mode signals and attenuates them at the output. Since no device is ideal, some of the applied differential signals are converted into the common mode and some of the common-mode signal is converted into the differential mode. This is referred to as mode conversion.

Differential components can have both common mode and differential mode signals, shown in figure 3.1, where d indicates differential mode and c indicates common mode. In most cases, the differential mode signals are anti-phase because their phase relative to each other is 180 degrees that creates a virtual ground along the axis of symmetry of the device. At the virtual ground, the potential at the operating frequency does not change with time, regardless of the signal amplitude.

Vector network analyzers are typically employed to measure RF components and are not designed for measuring differential parameters. Their RF ports are single-ended with common impedance values and cannot supply differential and common mode signals to a device.

Regarding reference impedance: single-ended devices have impedances of 50 to 75 ohms, while differential components have no standard impedance values. To measure a four-terminal (two-port differential) component requires 16 S-parameters, but these single-ended S-parameters are not sufficient to accurately characterize a differential component operating in differential mode. As a result, measuring differential components accurately using a single-ended analyzer cannot be accomplished without applying some type of hardware or software conversion to the single-ended data.

3.2 MIXED MODE S-PARAMETERS TRANSFORMATION

Mixed-mode S-parameters transformation uses a mathematical transform to convert the single-ended data to differential parameters [24],[17],[18]. This technique provides the common-mode and differential-mode parameters of the device. It is similar to single-ended measurement except that instead of stimulating a single terminal of the DUT, pairs of terminals are considered to be stimulated in either a differential (anti-phase) or a common (in-phase) mode. A physical differential/common mode stimulus to the device is not provided.

3.2.1 MIXED MODE S-PARAMETERS DEFINITION

The mixed mode S-parameters technique seeks to determine (with a differential mode stimulus on a differential port) the corresponding differential and common mode responses on all of the device ports. For a common-mode stimulus, the technique attempts to determine the differential-mode and common-mode responses. A mixed-mode S matrix can be organized in a similarly to the single-ended S-matrix, in which each column represents a different stimulus condition, and each row represents a different response condition. Unlike the single-ended S-parameters, the mixed mode S-matrix not only considers the port but the mode of the signal at each port. The definitions are shown in figure 3.2 and figure 3.4.

For four ports device:

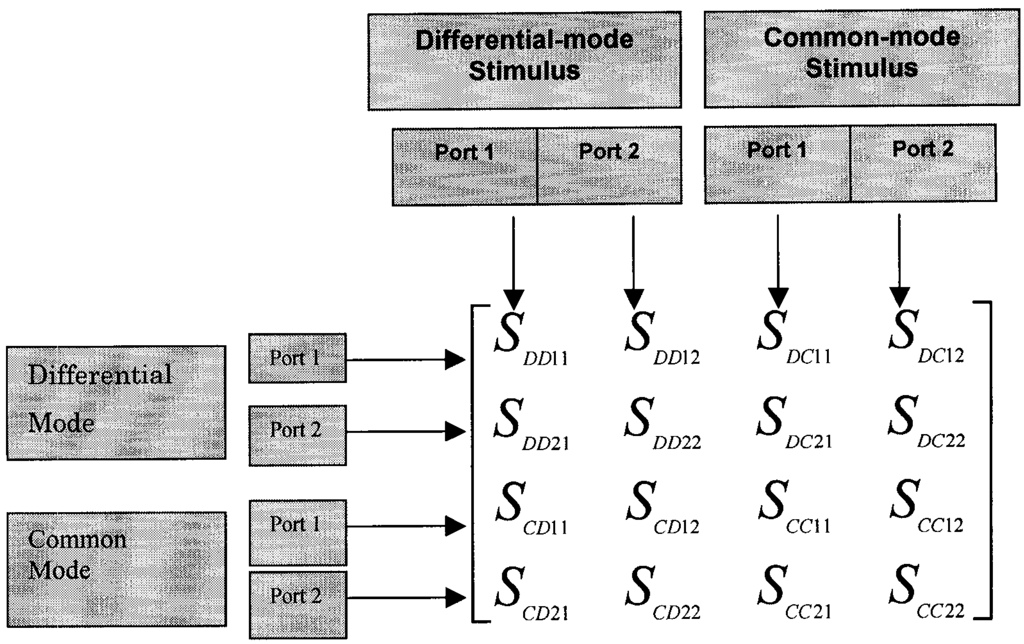

Figure 3.2 Definition of Four Port Mixed Mode S-Parameters

For three Ports Devices:

A simple extension of the mixed-mode concept can be applied to devices having a combination of differential and single-ended ports. The four-terminal matrix can be converted to a three-terminal matrix by removing the port 1 differential mode stimulus and response (figure 3.3). In this case, the differential and common modes on the differential ports and one mode on the single-ended port must be considered.

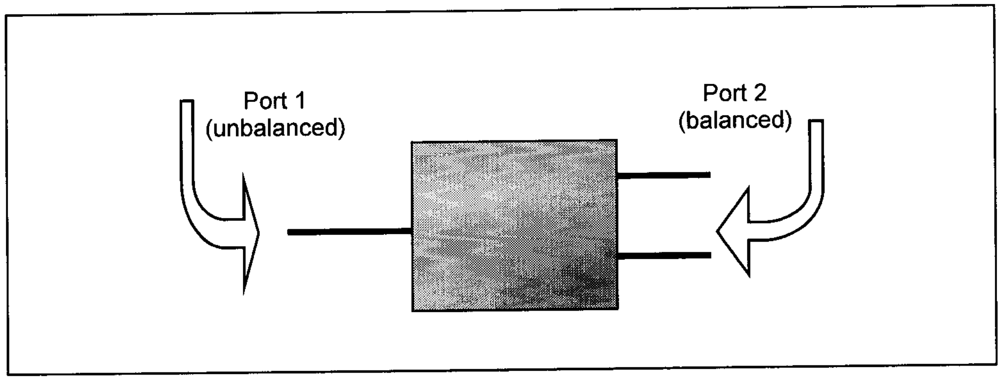

Figure 3.3 Three Port Device

The S-matrix for such a device is arranged with the stimulus conditions in the columns and the response conditions in the rows (figure 3.4). The mode on the single-ended port is referenced with 's' for single-ended instead of 'c' for common mode since only one mode is available on this port. Two columns and two rows describe each differential port, and one column and one row describe each single-ended port.

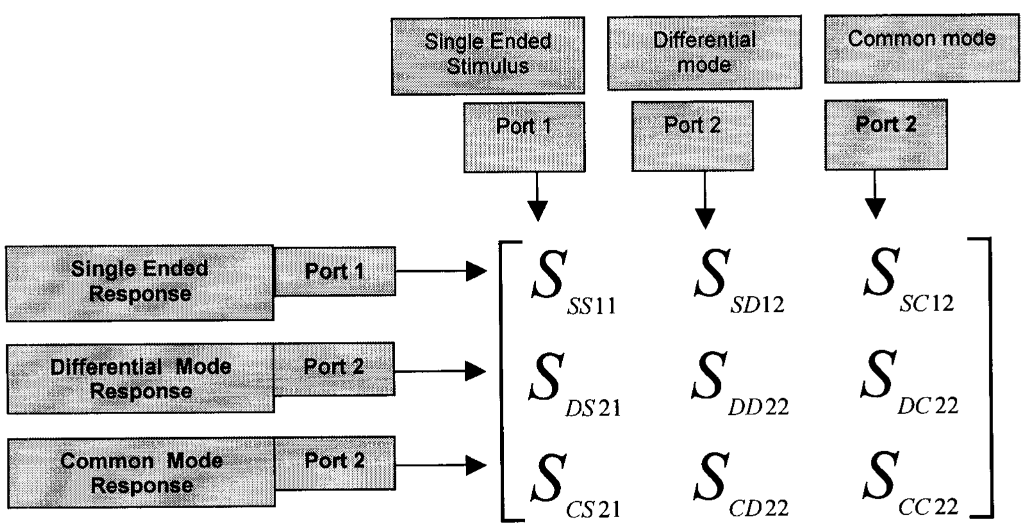

Figure 3.4 Definition of Three Port Mixed Mode S-parameters

3.2.2 MIXED MODE S-PARAMETERS CALCULATION

Bockelman and Eisenstadt [2], [4], have analyzed a method to convert the single-ended data to mixed-mode data using mathematical formulas. These formulas show the relationship between nodal waves generated by a standard vector network analyzer and the associated common and differential waves of mixed mode *S*-parameters.

This method is highly beneficial because of the quick and simple method of conversion. It does not require a circuit simulator and therefore can be performed in real time using a compiled math function library [17].

Balanced network is defined in figure 3.5. It can be viewed as either a four-port single-ended network or a two-port balanced network.

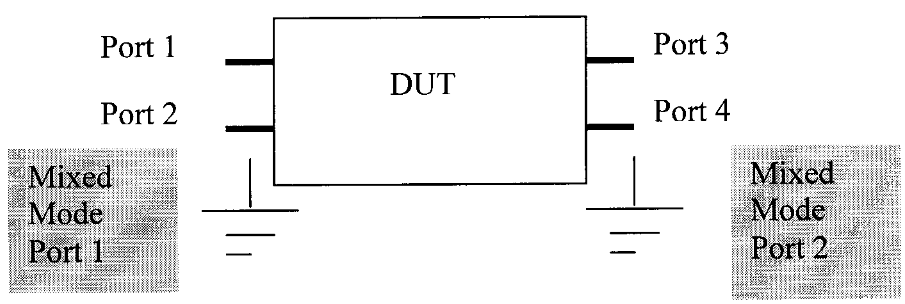

Figure 3.5 Balanced Network

To develop the transformation between standard S-parameters and mixed-mode S-parameters, let's review the mixed mode S-parameters definitions as shown in (3.1).

$$\begin{bmatrix} b_{d1} \\ b_{d2} \\ b_{c1} \\ b_{c2} \end{bmatrix} = \left[\begin{array}{c|c} S_{dd} & S_{dc} \\ \hline S_{cd} & S_{cc} \end{array}\right] \begin{bmatrix} a_{d1} \\ a_{d2} \\ a_{c1} \\ a_{c2} \end{bmatrix} \tag{3.1}$$

Each partition represents a two-by-two S-parameters sub matrix. The partition labeled Sdd is the differential mode S-parameters. Scc is the common-mode S-parameters. Sdc is the mode-conversion or cross-mode S-parameters that describes the conversion of common-mode waves into differential-mode waves. Lastly Scd describes the conversion of differential-mode waves into common-mode waves.

Together, these four sets of S-parameters simultaneously describe the combined differential and common-mode behavior of the test device. Hence, they are known as mixed mode S-parameters.

In (3.1), a_{di} and b_{di} are the normalized differential-mode stimulus and response waves, and a_{ci} and b_{ci} are the normalized common-mode stimulus and response waves. The definitions of these normalized waves for each mode are as follows:

$$a_{di} = \frac{1}{2\sqrt{R_d}}[v_{di} + i_{di}R_d] \tag{3.2}$$

$$a_{ci} = \frac{1}{2\sqrt{R_c}}[v_{ci} + i_{ci}R_c] \tag{3.3}$$

$$b_{di} = \frac{1}{2\sqrt{R_d}}[v_{di} - i_{di}R_d] \tag{3.4}$$

$$b_{ci} = \frac{1}{2\sqrt{R_c}}[v_{ci} - i_{ci}R_c] \tag{3.5}$$

The subscript indicates a port number. Here, v_{di} and i_{di} represent the differential-mode voltage and current at port, v_{ci} and i_{ci} are the common-mode voltage and current at the same port. R_d and R_c represent the differential and common-mode characteristic (or reference) resistances, respectively.

The mixed-mode S-parameters in (3.1) can be directly related to standard four-port S-parameters by examining the relations between mixed-mode normalized waves in (3.2) - (3.5) and traditional normalized waves. If nodes 1 and 2 are paired as a single differential port, and nodes 3 and 4 are also paired, the relation between single-ended and mixed mode traveling waves can be obtained by putting mixed mode voltage and current definitions into normalized power wave definitions.

$$a_{d1} = \frac{1}{\sqrt{2}}(a_1 - a_2) \tag{3.6}$$

$$a_{c1} = \frac{1}{\sqrt{2}}(a_1 + a_2) \tag{3.7}$$

$$b_{d1} = \frac{1}{\sqrt{2}}(b_1 - b_2) \tag{3.8}$$

$$b_{c1} = \frac{1}{\sqrt{2}}(b_1 + b_2) \tag{3.9}$$

$$a_{d2} = \frac{1}{\sqrt{2}}(a_3 - a_4) \tag{3.10}$$

$$a_{c2} = \frac{1}{\sqrt{2}}(a_3 + a_4) \tag{3.11}$$

$$b_{d2} = \frac{1}{\sqrt{2}}(b_3 - b_4) \tag{3.12}$$

$$b_{c2} = \frac{1}{\sqrt{2}}(b_3 + b_4) \tag{3.13}$$

Here a_i and b_i are the waves measured at port 1–4. By using the definition of S-parameters for a four-port network together with the relations in (3.6) to (3.7), a transformation between mixed-mode and standard S-parameters can be found.

The transformation can be developed by considering the relationships between the standard and mixed-mode incident waves, 'a', which can be written as

$$\begin{bmatrix} a_{d1} \\ a_{d2} \\ a_{c1} \\ a_{c2} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} \tag{3.14}$$

or $A_{mm}=MA_{std}$, where A_{mm} and A_{std} are the mixed-mode a-waves, respectively, and

$$M = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \tag{3.15}$$

Similarly, for the response waves b, it is found $B_{mm}=MB_{std}$. Applying the generalized definition of S-parameters B=SA, it can be shown that

$$S_{mm} = MS_{std}M^{-1} \tag{3.16}$$

where S_{mm} are the mixed-mode S-parameters and S_{std} are the standard four-port S-parameters. Additionally, M has the property $M^{-1}=M^{T}$.

The transformation in (3.16) gives additional insight into the nature of mixed-mode S-parameters. It is a straightforward transformation that indicates that a change of basis has occurred between standard and mixed-mode S-parameters. Furthermore, it clearly indicates that the two sets of S-parameters are different representations of the same device, and that ideally, the two representations contain the same information about the device.

3.3 MIXED MODE S-PARAMETERS MEASUREMENT

The existence of a transformation between standard and mixed-mode S-parameters suggests two possible approaches to the measurement of differential circuits.

One approach is the use of a traditional two-port VNA. A traditional VNA would measure standard S-parameters by stimulating each terminal of the differential circuit individually [17]. These S-parameters would then be transformed to mixed-mode parameters for analysis.

Alternatively, the mixed-mode S-parameters of the differential circuit can be measured directly by stimulating each mode individually [27].

In this project, calibration of the developed differential tuners and fixture, as well as baluns, can be done by measuring single-ended four-port or three port S-parameters. And mixed mode S–parameters are computed by applying mathematic transformation we discussed earlier.

The other components in the setup can be calibrated by measuring standard S-parameters. Once mixed or differential mode S-parameters are obtained, all measurement data can be de-embedded to the DUT reference plane.

Mixed mode S-parameters can be cascaded as the single ended S-parameters. The rules of gain calculation still can be applied to mixed mode S-parameters.

3.4 CONCLUSION

Mixed S-parameters give a complete insight to the balanced circuit. The transformation formula between single-ended S-parameters and balanced S-parameters make the measurements easier by using existing unbalanced instruments.

CHAPTER 4
LOAD PULL THEORY

4.1 INTRODUCTION

Load Pull and Source Pull measurements are impedance related measurements [10]. This means that the main independent parameter of the measurement is not frequency, power, bias, or even temperature, vibration or pressure. The main independent parameter is the Source or Load Impedance (or Reflection Factor) at the fundamental or any harmonic frequency, presented to the Device Under Test (DUT).

These impedances are normally generated using a TUNER, which is a passive component that changes the impedance, at a given frequency, as a function of the position of its internal components. This method is called Passive Load Pull.

The method of generating the impedance virtually, i.e. by re-injecting, at the output of the DUT, the signal after having modifying its amplitude and phase using 'active circuits' (circuits with gain), was first proposed in the 1970's and is generally called Active Load Pull.

Tuner measurements have been used from the beginning of the microwave technology. However, it was not possible to visualize the impedance conditions during the measurement until the mid 1970's, where the first Automatic Load Pull System became available at RCA David SARNOFF Research Laboratory in N. Jersey. This system operated using a model to compute the impedance of the tuners as a function of their geometry and position. Many other laboratories have developed and published semi-automatic or automatic tuner systems, but RCA's system was the first one to become commercialized in the early 1980's.

4.2 TYPICAL LOAD PULL CONFIGURATION

A typical load pull configuration is shown in figure 4.1.

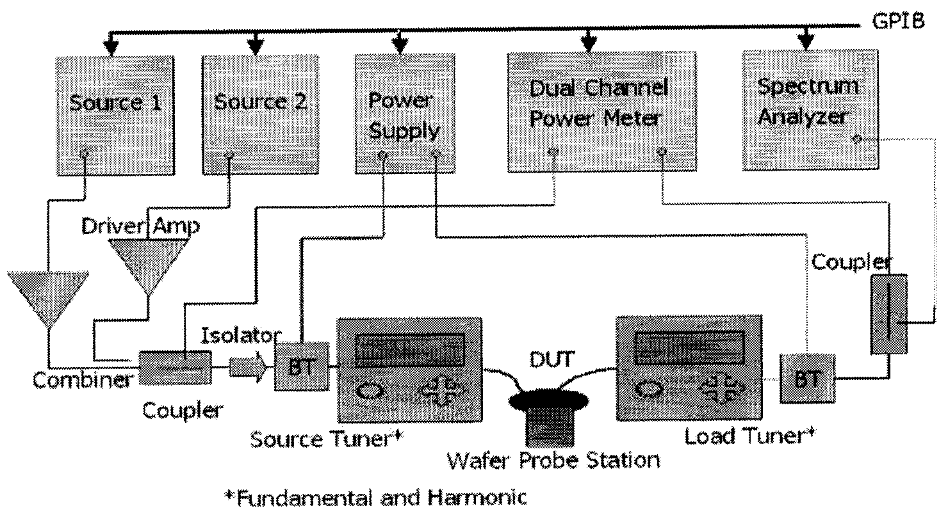

Figure 4.1 Load Pull Configuration

4.2.1 INSTRUMENTS

The instruments required in the configuration depend on the RF parameters that will be measured. Usually power meters, power supply, signal generator, spectrum analyzer and VNA (Vector network analyzer) are essential for the basic load pull system. Other instruments may be needed if specific RF parameters need to be measured, EVM measurement for instance.

4.2.2 TUNERS

For basic load pull operation, two standard microwave tuners are needed. One is used to match the input of the device, while another one (output tuner) is used to match the output of the device. If the harmonic information is of concern, harmonic tuners can be added into the load pull system between DUT and tuners.

4.2.3 COMPONENTS

Couplers, isolators, attenuators, bias tees and test fixtures are embedded into the load pull system.

Directional Couplers are used to measure the injected power at the input and output. Usually an isolator is needed following the input coupler or the coupling could change with source tuning. This also holds true for the output coupler but is less important since it is not on the direct power measurement path.

Isolators have limited bandwidth outside of which they may have significant reflection. A 3dB attenuator can be used after the input isolator to reduce this problem. If you include the reverse isolation data of the couplers then you can eliminate the need for an isolator.

Focus Microwaves load pull system setup is shown in figure 4.2.

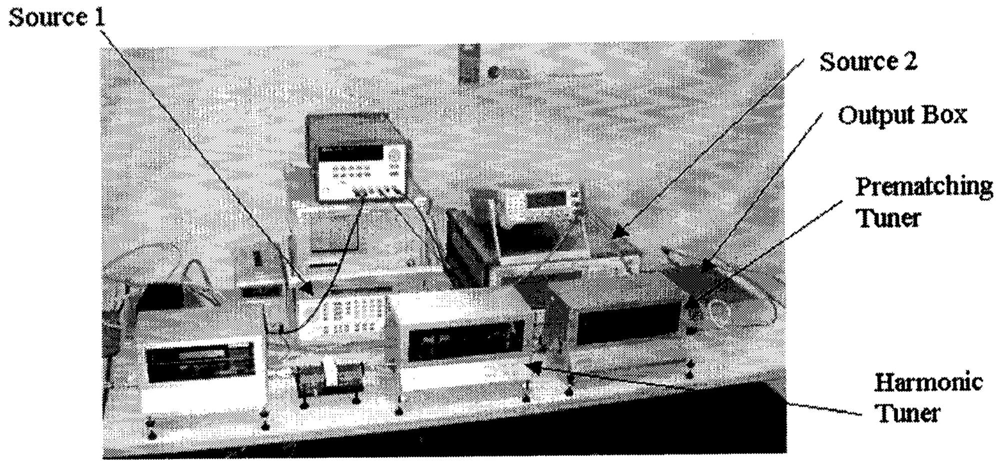

Figure 4.2 The Real Load Pull System

4.3 DIFFERENTIAL LOAD PULL SYSTEM

The Differential Load Pull system shown in figure 4.3 is a measurement system in which the differential Load (or Source) impedance is modified by using a differential tuner.

The unbalanced signal of the input is split into two unbalanced signals (differential signal) by the input balun, and then injected into a differential device through a differential tuner and the input part of the differential test fixture. The differential signal, amplified by the DUT, is delivered to an output differential test fixture and tuner, and finally transformed by the output balun to an unbalanced signal, which can be measured directly by standard unbalanced power meter, spectrum analyzer and other instruments.

A Network Analyzer is not used in the setup, since all components have to be pre-calibrated. The losses of the baluns, differential tuners, and differential test fixtures are calculated from mixed mode S-parameters. All RF parameter data of the DUT is eventually extracted by de-embedding the losses. Optimum complex reflection coefficient of source and load can also be obtained by straightforward mathematic calculations.

The PC is used both to control the DMT tuners and to communicate with all instruments by IEEE 488.2 GPIB bus. The software is developed in C++, which is capable of controlling tuners, acquiring data from instruments as well as parameters extraction.

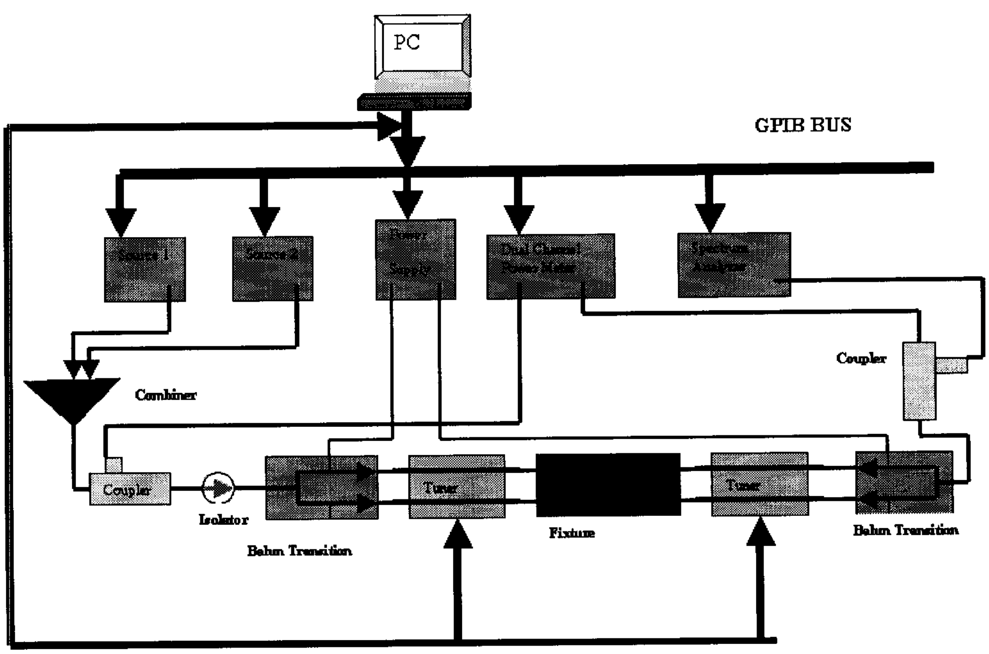

Figure 4.3 Differential Load Pull System

The developed differential load pull system was built and is shown in figure 4.4. The details are discussed in the following chapters.

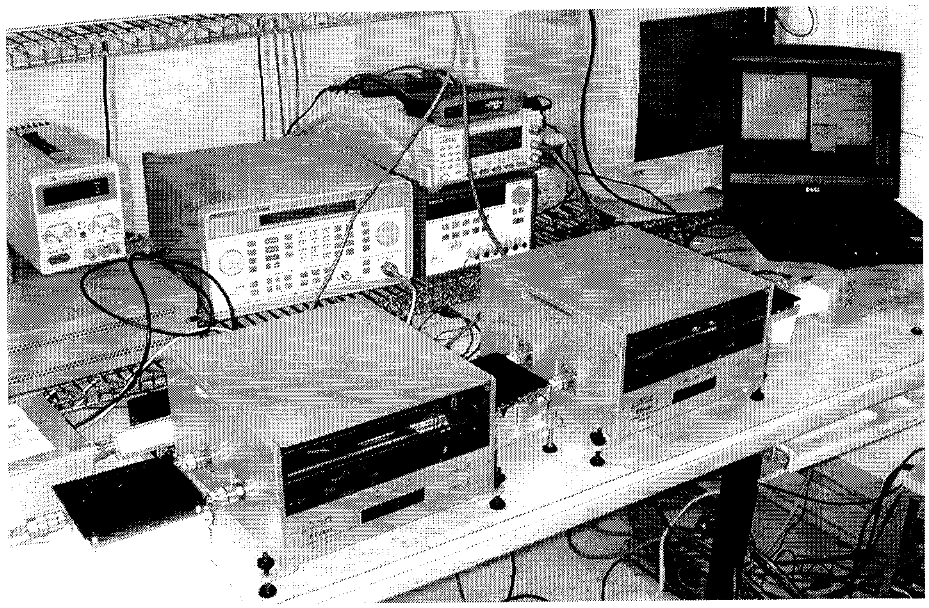

Figure 4.4 The Real Differential Load Pull System

4.4 DIFFERENTIAL LOAD PULL SYSTEM COMPONENTS AND COMPUTATION

Special components were designed for the differential load pull system, including DMTs (Differential Microwave Tuners), Microwave Balun transition boards, and DTFs (Differential Test Fixtures). They are addressed in detail in the following chapters. The objective of the measurement is to get the power and other desired parameters' values at the DUT reference plane. DMTs, DTFs, and Baluns as well as other components generate losses, which vary with the tuner position. For example, the loss increases significantly if tuner is tuned to very high reflection coefficients.

In order to obtain the right (true) value at the DUT, the losses must be added or extracted from the raw measurement data. To get the available input power at the DUT reference plane, the available loss of the input is subtracted from the calibrated available input power, which is measured by an input power meter through coupling port of the input coupler. To get the delivered output power at the DUT reference plane, the losses of the output are also de-embedded.

4.5 CONCLUSION

Differential load pull systems are based on the standard load pull systems except for the fact that balanced (differential) devices are characterized rather than single-ended two-port devices.

In single-ended load pull systems, S-parameters are used to calibrate the setup, while Mixed Mode S-parameters are used to calibrate the differential load pull system.

CHAPTER 5
SYSTEM SIMULATION

5.1 INTRODUCTION

In this chapter several simulations have been done using Agilent ADS simulator [28], [29]. The purpose of these simulations is the following:

The reference impedance of the system needs to be defined. Secondly, simulations are used as a tool to verify the transformation formulas introduced in chapter 3. Finally, load pull simulations help to prove the concept of a differential load pull system.

5.2. REFERENCE IMPEDANCE

The reference impedance of the differential mode can be derived from the definition of the mixed mode S-parameters.

Z_{dn} is the differential-mode characteristic impedance at port n (Z_{oo}), and Z_{cn} is the common-mode characteristic impedance at port n (or Z_{oe}). In order to make the conversion from single ended S-parameters to mixed-mode S-parameters an assumption is made that the DUT is being fed from differential input lines, and that $Z_{oe} = Z_{oo} = Z_0$. The assumption of differential input lines is not limiting, since the lengths of these lines can be defined to be arbitrarily small. The assumption of $Z_{oe} = Z_{oo} = Z_0$ implies that the differential input lines are not coupled [5].

This is also valid in the DLPS system, since the feed lines are the two slab lines of either the input or output tuner. They are in fact completely isolated. So the differential mode impedance should be:

$$\boxed{\begin{matrix} Z_d = 2Z_o \\ Z_c = Z_o/2. \end{matrix}}$$

A circuit simulator ADS is used to measure mixed-mode S-parameters of the differential device. A center-tapered balun is configured to perform the differential mode conversion and also provides the mechanism for the common-mode terms. The three-port device is a real balun from Anaren [36]. The common mode conversion occurs at the center tap of the balun where only common-mode signals will appear because of the characteristics of the balun. These common-mode signals are then terminated through a balun into a 25-ohm termination, which is the common-mode impedance.

Two 25 to 50 ohm transformers are embedded to the setup in order to match the 25-ohm port impedance to the tuner's 50-ohm slab line.

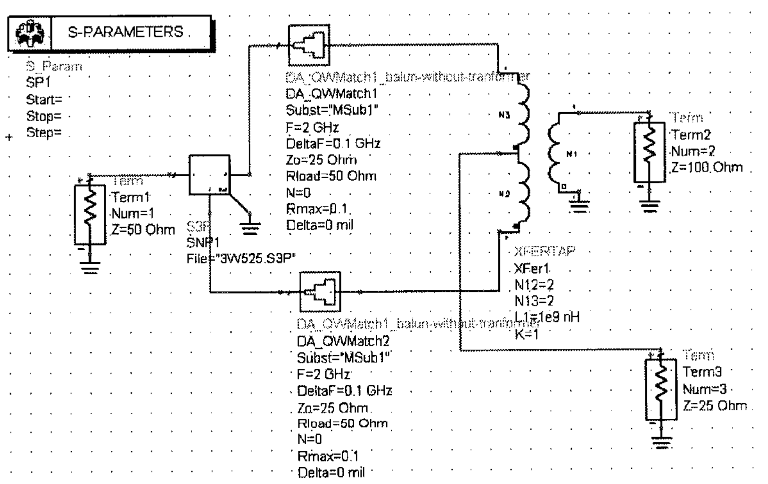

Figure 5.1 Reference Impedance Simulation Circuit

The simulation circuit is shown in figure 5.1. Single ended 3 port S-parameters of a balun are input to the circuit by creating a 3-port component. The working frequency is 2 GHz. The format of the S-parameters is MA (Magnitude and Phase).

$$\begin{bmatrix} 0.2086\angle 82.42 & 0.6656\angle -133.49 & 0.6772\angle 44.57 \\ 0.6647\angle -133.41 & 0.5808\angle 154.36 & 0.4125\angle 133.27 \\ 0.6765\angle 44.64 & 0.4124\angle 133.29 & 0.5574\angle 151.25 \end{bmatrix}$$

Mixed Mode S-parameters are simulated and the results are shown on below.

$$\begin{bmatrix} S_{SS11} & S_{SD12} & S_{SC12} \\ S_{DS21} & S_{DD22} & S_{DC22} \\ S_{CS21} & S_{CD22} & S_{CC22} \end{bmatrix} = \begin{bmatrix} 0.134\angle -74.5 & 0.966\angle 135.7 & 0.024\angle -143.9 \\ 0.964\angle 135.8 & 0.138\angle 162.6 & 0.024\angle 10.03 \\ 0.024\angle -143.7 & 0.025\angle 10.45 & 0.949\angle -68.9 \end{bmatrix}$$

At differential termination (2) with 100-ohm impedance termination, the return loss is pretty good ($0.138\angle 162.2$). The reflection at common mode termination (3) is very high ($0.949\angle$-168.9.) Differential mode to common mode conversion is very low. This is shown by the dc mode conversion parameter S_{dc} ($0.025\angle 10.45$.)

An alternative way to simulate differential mode S-parameters is to connect 100 Ohm floating termination at the balanced port directly. The simulation circuit is shown in figure 5.2.

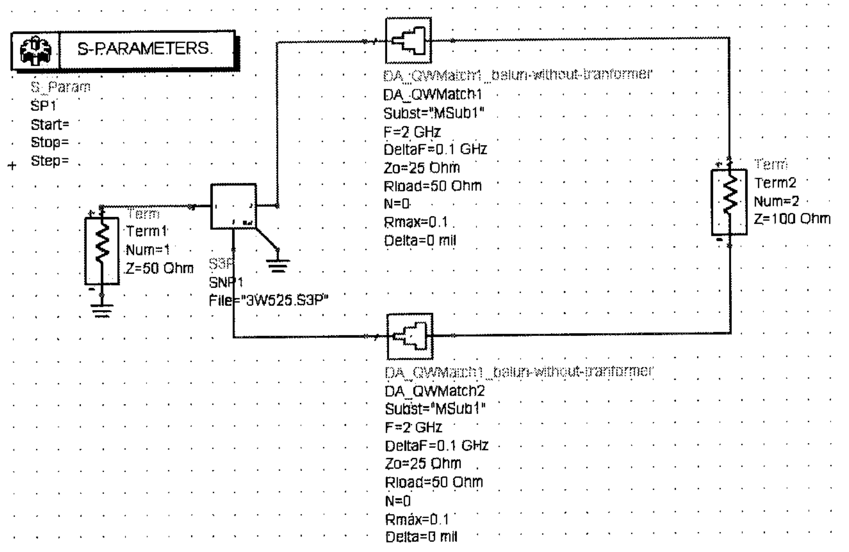

Figure 5.2 Differential Impedance Simulation Alternative

The result of this differential mode S-parameters two port is the following:

$$\begin{bmatrix} S_{ss11} & S_{sd12} \\ S_{ds21} & S_{dd22} \end{bmatrix} = \begin{bmatrix} 0.134\angle -74.4 & 0.967\angle 135.8 \\ 0.966\angle 135.9 & 0.137\angle 162.7 \end{bmatrix}$$

The simulation results show that the 100Ohm is the reference impedance at differential mode in the differential load pull system.

5.3. MIXED MODE TRANSFORMATION VERIFICATION

Next study will focus on mixed mode S-parameter calculation in detail. The conversion formula will be verified.

First of all, the three-port single ended S-parameters are simulated. The components include one ideal transformer and two micro-strip transformers. The 1:1 transformer is used as an ideal balun, and micro-strip transformers match 25 ohms to 50 ohms.

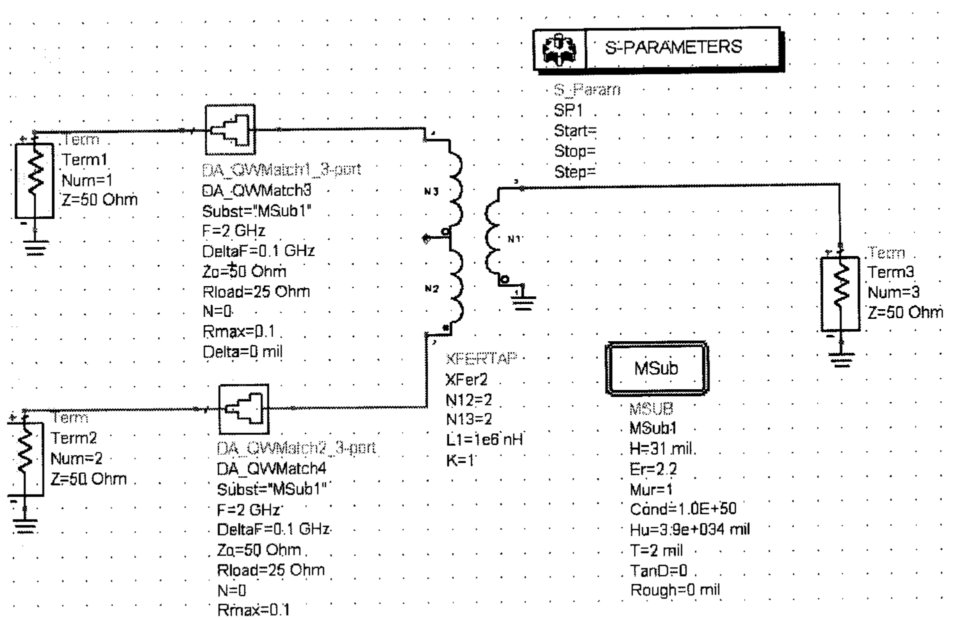

Figure 5.3 Single Ended Three Port Simulation

The simulated S-parameters result is the following,

$$[S]=\begin{bmatrix} 0.507\angle 1779.334 & 0.493\angle 178.877 & 0.707\angle -90.678 \\ 0.493\angle 178.877 & 0.507\angle 179.334 & 0.707\angle 89.322 \\ 0.707\angle -90.678 & 0.707\angle 89.322 & 0.014\angle 162.642 \end{bmatrix}$$

Next, the differential modes S-parameters are simulated. The simulation circuit is shown in figure 5.4.

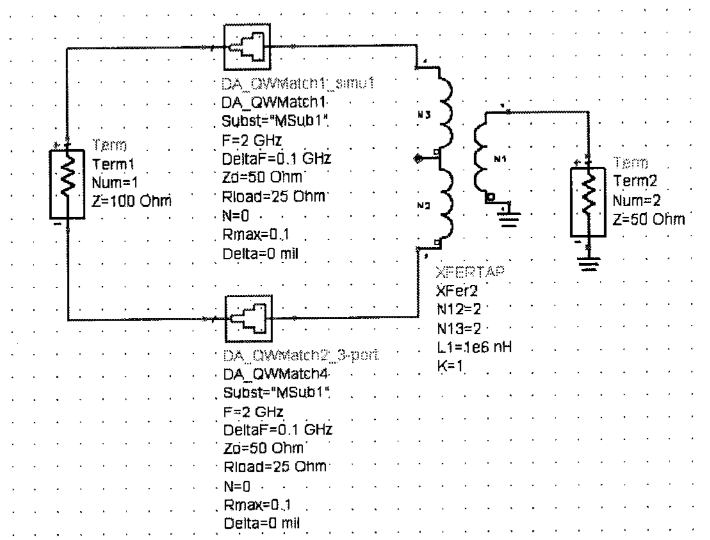

Figure 5.4 Mixed Mode S-Parameters Simulation

The differential mode S-parameters are simulated and the following results were obtained:

$$[S]=\begin{bmatrix} 0.014\angle-163.997 & 1.000\angle-90.678 \\ 1.000\angle-90.678 & 0.014\angle162.642 \end{bmatrix}$$

The formulas used to calculate mixed mode S-parameters from three port single ended S-parameters are the following:

$$S_{1d}=\frac{1}{\sqrt{2}}(S_{12}-S_{13}) \tag{5.1}$$

$$S_{1c}=\frac{1}{\sqrt{2}}(S_{12}-S_{13}) \tag{5.2}$$

$$S_{d1}=\frac{1}{\sqrt{2}}(S_{21}-S_{31}) \tag{5.3}$$

$$S_{c1}=\frac{1}{\sqrt{2}}(S_{21}-S_{31}) \tag{5.4}$$

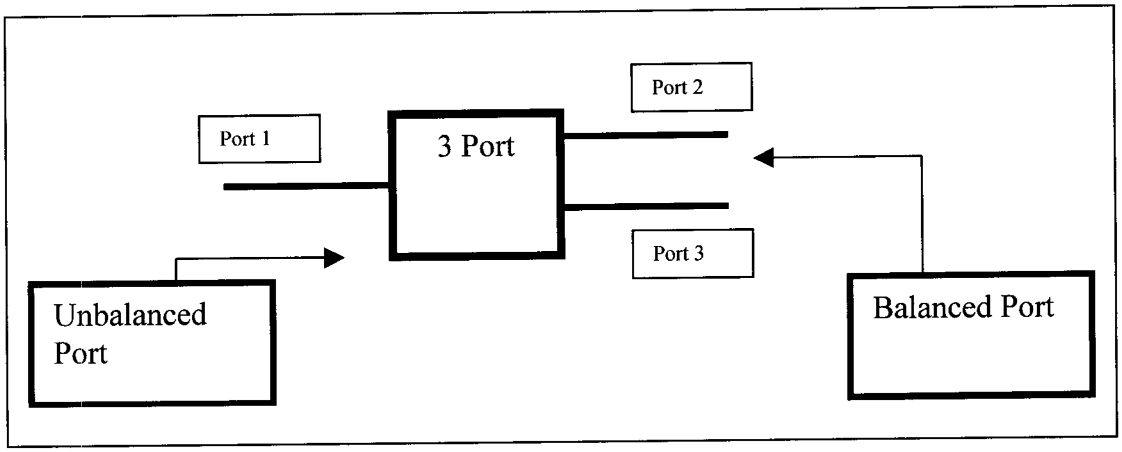

Figure 5.5 Three-Port Networks

$$S_{dd} = \frac{1}{2}(S_{22} - S_{23} - S_{32} + S_{33}) \tag{5.5}$$

$$S_{cc} = \frac{1}{2}(S_{22} + S_{23} + S_{32} + S_{33}) \tag{5.6}$$

$$S_{dc} = \frac{1}{2}(S_{22} + S_{23} - S_{32} - S_{33}) \tag{5.7}$$

$$S_{cd} = \frac{1}{2}(S_{22} - S_{23} + S_{32} - S_{33}) \tag{5.8}$$

The results calculated by transformation formula 5.1—5.8 are in agreement with mixed mode simulation results obtained through ADS simulation.

5.4. SINGLE ENDED LOAD PULL SIMULATION

Load pull measurements are simulated in ADS in this section. Firstly, a standard single-ended load pull is simulated. The purpose of a single ended load pull simulation is to compare it with a differential load pull simulation in order to demonstrate a feasible configuration of the Differential Load Pull

System. Notice that all harmonic impedances are set at 50 Ohm in the simulation.

5.4.1 DEVICE SELECTION

Since the purpose of the simulation is to explore the concept of a differential load pull system, the type of device in the simulation is not important. In other words, the concept of the DMT tuners, as well as the calibration procedure should be verified.. Thus the device used in the simulation circuit is a MOSFET, with an existing model in ADS.

5.4.2 SIMULATION CIRCUIT

The simulation setting and simulation circuit is shown in figure 5.6.

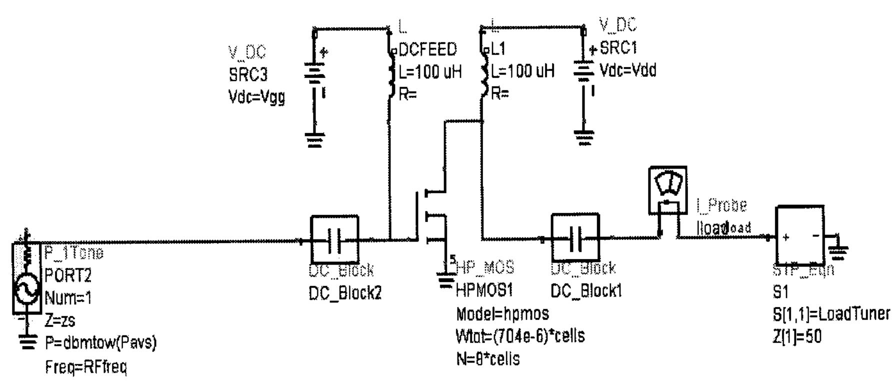

Figure 5.6 Single Ended load pull simulation circuit

5.4.3 SIMULATION RESULT

The single load pull simulation result is shown in figure 5.7.

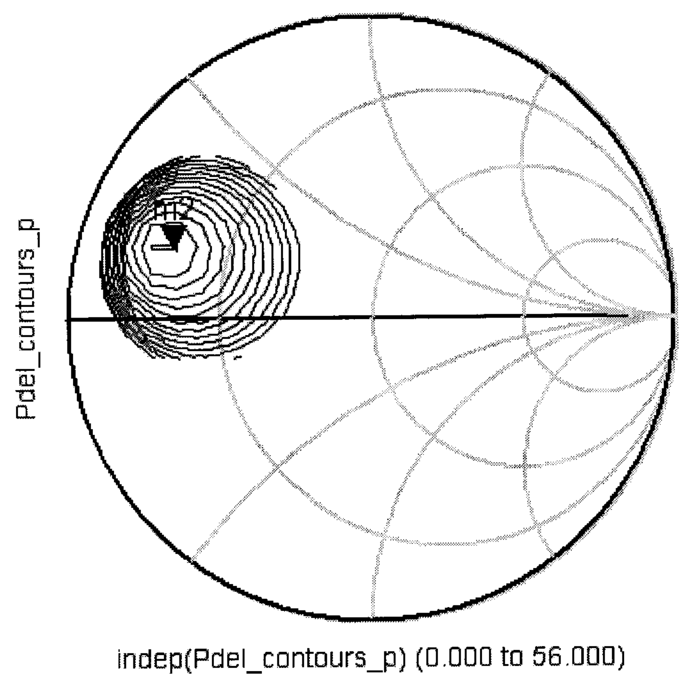

Figure 5.7 Single Ended load pull Simulation Results

Optimum impedance is at gamma 0.691 ∠ 159.4. (9.4 + j* 8.77 ohms) Output power is 20.8 dBm.

5.5 DIFFERENTIAL LOAD PULL SIMULATION

Differential device is constructed by combining two identical transistors that are the same devices as in the Single Ended load pull simulation.

5.5.1 DIFFERENTIAL DEVICE

The differential device is shown in figure 5.8. Two MOSFET devices are connected in series that simulates the push pull device.

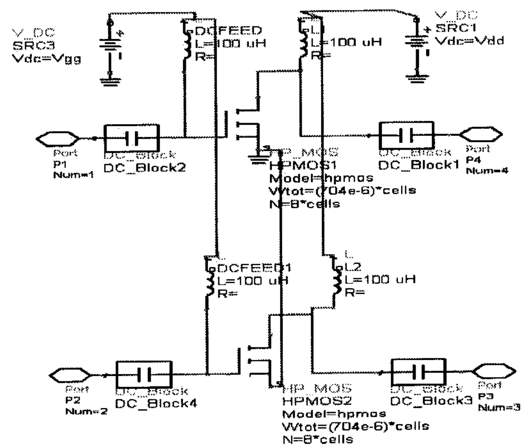

Figure 5.8 Push Pull Load Pull Simulation Device

5.5.2 SIMULATION

Two ideal baluns are used in the circuit to convert an unbalanced signal to a balanced signal. These balanced signals are combined by output balun back to an unbalanced signal. Micro-strip transformers are used to match the 25-ohm impedance at each balanced port to 50-ohm. It is very important since reflection factor generated by DMT should cover the whole the Smith Chart.

The simulation circuits are shown in figure 5.9.

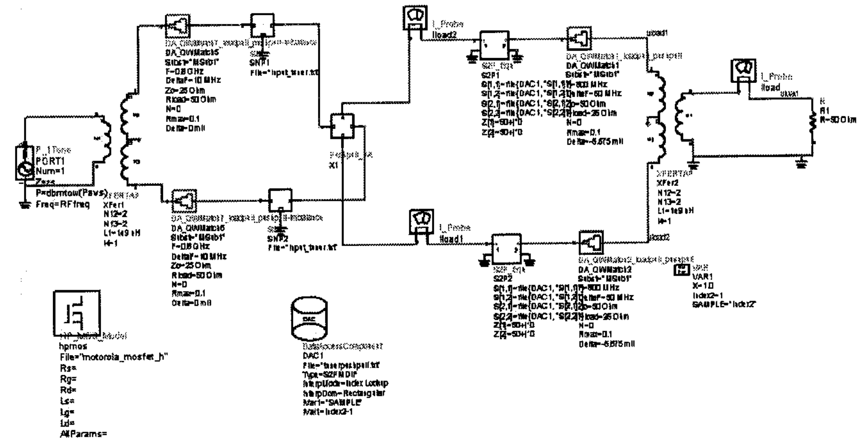

Figure 5.9 Push Pull Load Pull Simulation Circuit

5.5.3 DIFFERENTIAL LOAD PULL SIMULATION RESULT

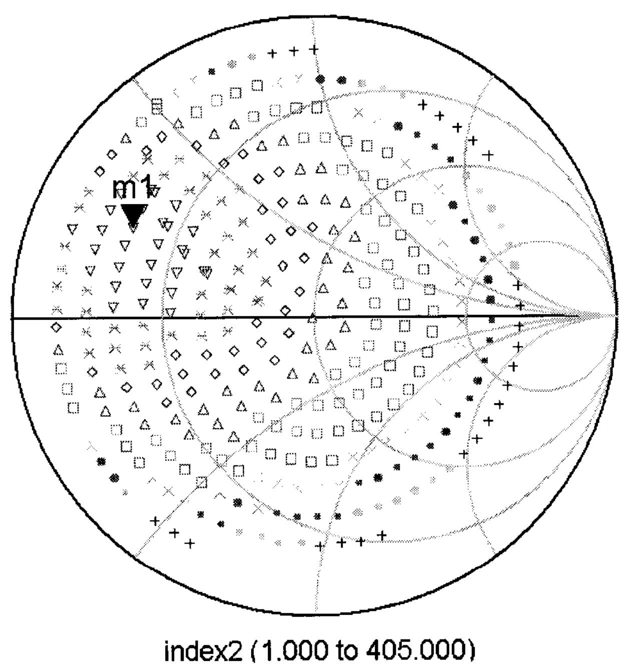

Figure 5.10 Push Pull Load Pull Simulation Result

The results show that:

Optimum Impedance: 20.48+ j* 17.73 Ohms
Optimum reflection factor: 0.669 <159.06.
Maximum output power: 23.8 dBm.

5.6 CONCLUSION

Differential load pull simulation shows that output power of push pull device is twice that of the single ended device. The optimum load impedance is around twice as large as the single ended device.

The differential load pull system, configured as in the above simulation circuit works conceptually. Furthermore, it shows that the differential system is feasible to be implemented in this manner.

CHAPTER 6
DIFFERENTIAL MICROWAVE TUNER AND TEST FIXTURE DESIGN

Differential Microwave Tuners and Differential Test Fixtures are designed to characterize differential microwave devices.

6.1 DIFFERENTIAL TUNER INTRODUCTION

DMT is an electromechanical instrument that allows precise positioning of probes in two 50-Ohm slotted transmission lines [30], shown in figure 6.1, to generate repeatable complex microwave reflection factors.

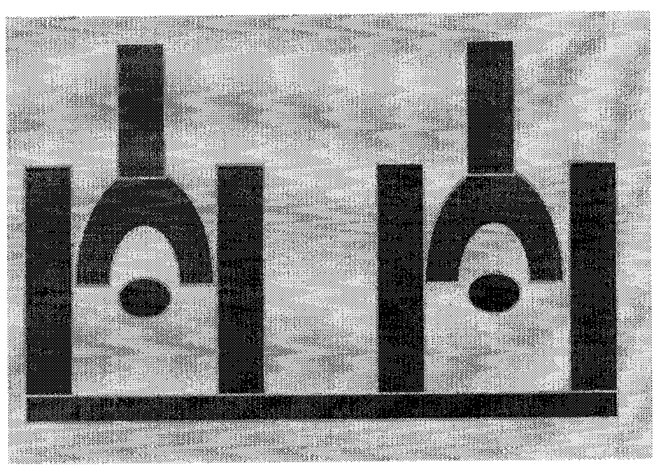

Figure 6.1 Principle of RF Probes in Slotted Airlines

The positioning of the probes is obtained using computer controlled stepper motors and two vertical and two horizontal screw translation mechanisms driven by timing belts. DMT tuners use the vertical anti-backlash mechanism with a resolution of 1.5 micrometer per motor step (closest distinguishable positions). Horizontally the step size varies between 3 and

25μm depending on the frequency of operation (3μm for tuners above 18 GHz, 25μm for tuners below 3 GHz and other values for operation in between). This choice is made in order to obtain an optimum "tuning speed/resolution" ratio. The use of timing belts to control axis positioning reduces any vibrations translated from the stepping motors to the axis and thus to the probes (in case the tuners are used on a probe station).

6.2 DMT STRUCTURE

DMT tuners are based on two precise parallel slotted coaxial airlines with four stepping motors controlling two slugs moving along, in, and out of the slots. The slugs are specially designed to allow extremely high reproducibility of setting position due to their vibration insensitivity and their removal of corrosion deposits after long periods of non-operation. High-resolution stepper motors with anti-backlash drives ensure exact mechanical positioning. High precision electrical switches guarantee zero positioning accuracy of better than ±1 motor step, both in horizontal and vertical directions.

Moving the slug up/down or left/right, the impedances presented at the two ports of each slab line are changed, and then the total impedance presented into the device (gate to gate or drain to drain) can be tuned. The total impedance can be calculated very accurately by using mixed mode S-parameters.

The mechanical structure is shown in figure 6.2. Two slab-lines, two carriages, four step motors, and four connectors as well as the tuner's support base are shown clearly in the drawing.

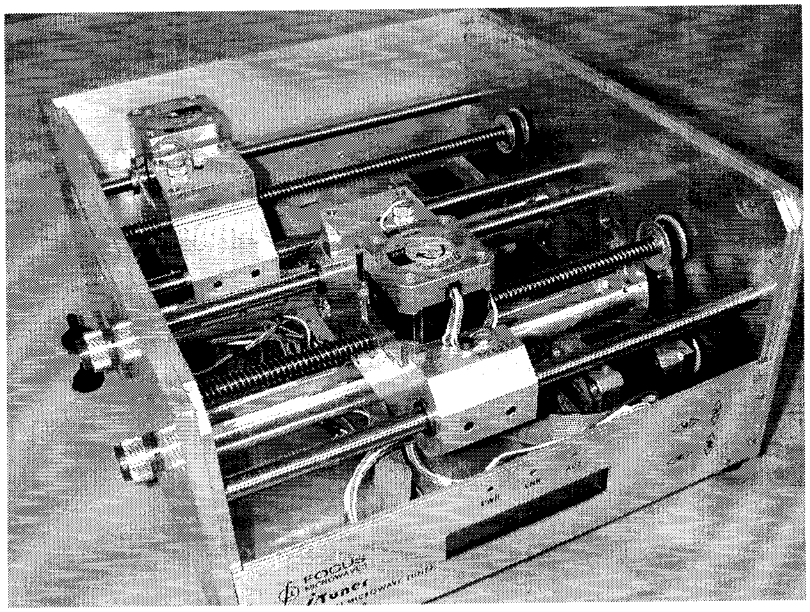

Figure 6.2 DMT Mechanism

The DMT prototype is manufactured at Focus Microwaves, and shown in the figure 6.3.

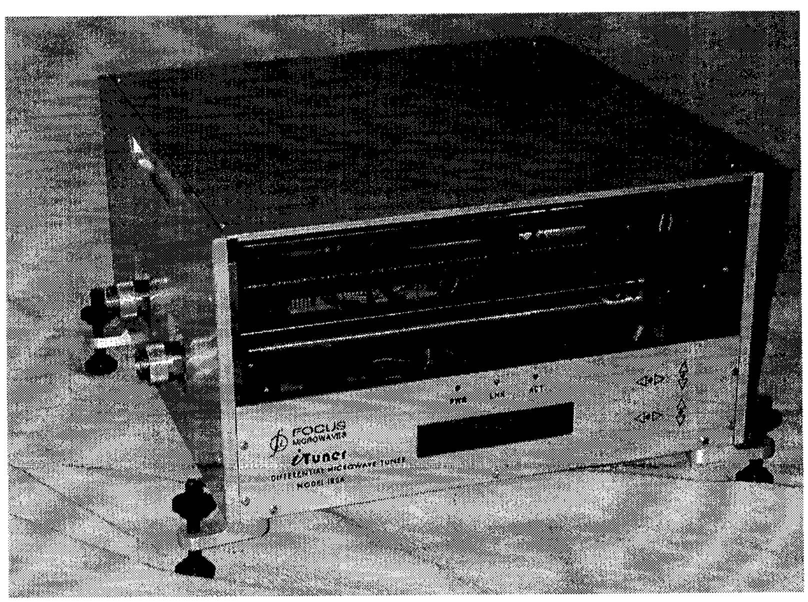

Figure 6.3 DMT Tuner

6.3 DMT IMBALANCE

Since the DMT tuner has two slab lines that present reflection factor to two paths of a differential signal, it is essential to study the effect of the imbalance created by these two slab lines.

When connecting two slab lines to a balun, the balun may work at imbalance condition, which is created by the Differential Tuner. Under this circumstance, common-mode signals will be produced due to both common mode to common mode transmission and differential mode to common mode conversion.

First of all a balanced configuration is simulated, which consists of a balun, two 25 ohm to 50 ohm transformers, and a four-port component representing a differential tuner. Four ports S–parameters contained in this component are measured from a slab line. Then an ideal transmission line is added at one signal path to create imbalance. Two cases are simulated, and common mode and differential mode S- parameters are compared. A balanced simulation circuit is shown in figure 6.4, while the results of mixed-mode S-parameters are shown figure 6.5.

Common mode S-parameters are as follows:

$$\begin{bmatrix} S_{cc11} & S_{cc12} \\ S_{cc21} & S_{cc22} \end{bmatrix} = \begin{bmatrix} 0.486\angle -17.25 & 0.019\angle 70.31 \\ 0.019\angle 73.82 & 0.978\angle 163.04 \end{bmatrix}$$

Differential mode S-parameters are as follows,

$$\begin{bmatrix} S_{dd11} & S_{dd12} \\ S_{dd21} & S_{dd22} \end{bmatrix} = \begin{bmatrix} 0.486\angle -17.25 & 0.856\angle 166.72 \\ 0.857\angle 166.73 & 0.482\angle 167.12 \end{bmatrix}$$

The differential mode to common mode conversion Scd is,

$0.003\angle 100.23$

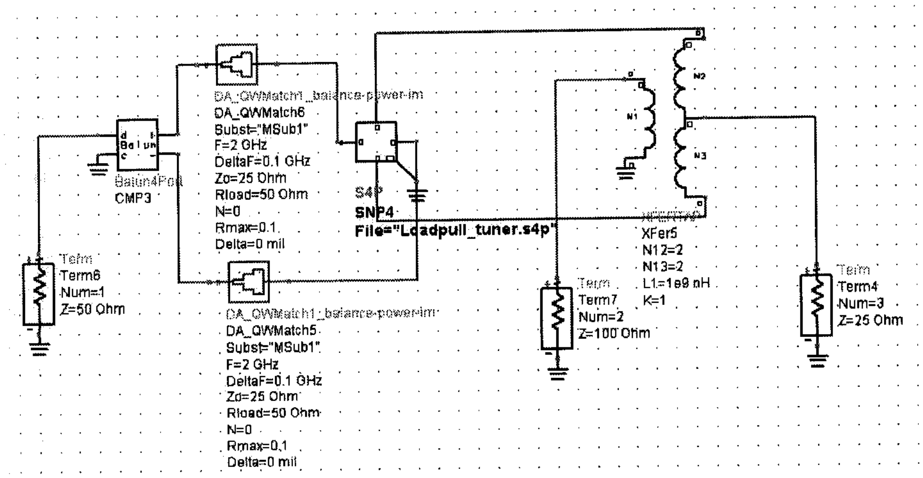

Figure 6.4 DMT Balanced Simulation Circuit

	freq	S
S(1,1)	2.000GHz	0.486 / -17.257
S(1,2)	2.000GHz	0.856 / 166.725
S(1,3)	2.000GHz	0.019 / 70.311
S(2,1)	2.000GHz	0.857 / 166.738
S(2,2)	2.000GHz	0.482 / 167.129
S(2,3)	2.000GHz	0.004 / 110.676
S(3,1)	2.000GHz	0.019 / 73.826
S(3,2)	2.000GHz	0.003 / 100.226
S(3,3)	2.000GHz	0.978 / 163.040

Figure 6.5 DMT Simulation Result of Balanced Case

The balanced case simulation shows that there are -34 dB attenuations for common mode signal, and -50 dB for mode conversion. The common mode signals are small enough to be neglected.

The same simulation is repeated except adding a ideal transmission line with electrical phase of 40 degrees. The simulation circuit and result are shown in figure 6.6 and figure 6.7.

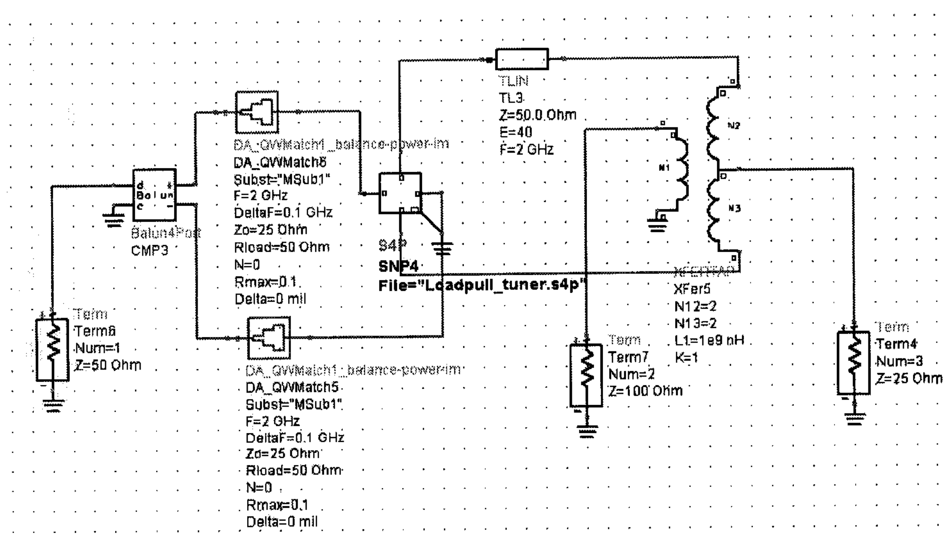

Figure 6.6 DMT Simulation Circuit of Imbalance Case

In this case, the common mode S-parameters are as follows,

$$\begin{bmatrix} 0.486\angle -17.25 & 0.311\angle 56.57 \\ 0..311\angle 56.35 & 0.805\angle 122.67 \end{bmatrix}$$

Differential mode S-parameters are as follows,

$$\begin{bmatrix} 0.486\angle -17.25 & 0.797\angle 146.78 \\ 0.799\angle 146.76 & 0.310\angle 128.44 \end{bmatrix}$$

	freq	S
S(1,1)	2.000GHz	0.486 / -17.257
S(1,2)	2.000GHz	0.797 / 146.778
S(1,3)	2.000GHz	0.311 / 56.349
S(2,1)	2.000GHz	0.799 / 146.762
S(2,2)	2.000GHz	0.310 / 128.440
S(2,3)	2.000GHz	0.471 / 34.602
S(3,1)	2.000GHz	0.311 / 56.570
S(3,2)	2.000GHz	0.471 / 34.516
S(3,3)	2.000GHz	0.805 / 122.668

Figure 6.7 DMT Simulation Result of Imbalanced Case

The mode conversion term, Scd is
$0.471\angle 34.51$

The imbalance simulation results show that differential mode common mode conversion (S32) increase from –50 dB to –6.5 dB, while the common mode transmission term (S31) is also up to –10 dB. The differential mode transmission term is 1.9 dB.

Come to a conclusion, the imbalance at the two arms of the signal will result in produce of common mode signals. The Differential Load Pull system cannot measure both common mode and differential mode signals at the same time; instead it characterize device only in differential mode. It is very important to avoid any imbalance in the entire setup.

The imbalance caused by the transmission phase of slab lines is determined by physical length of the two slab lines, which is impossible to adjust after the DMT tuners are manufactured.

Thus in order to avoid common mode signals from coming into play in the measurement, the DMT tuner should be balanced during manufacturing. The next section discusses the transmission phase adjustment.

6.4 TRANSMISSION PHASE ADJUSTMENT

One of the two slab lines is designed to be adjustable. The structure is shown below in Figure 6.12. By connecting two slab lines to a Vector Network Analyzer, the transmission phase of the two slab lines can be observed. By adjusting the moveable part of one slab line, the transmission phase of the two lines can be tuned to be identical.

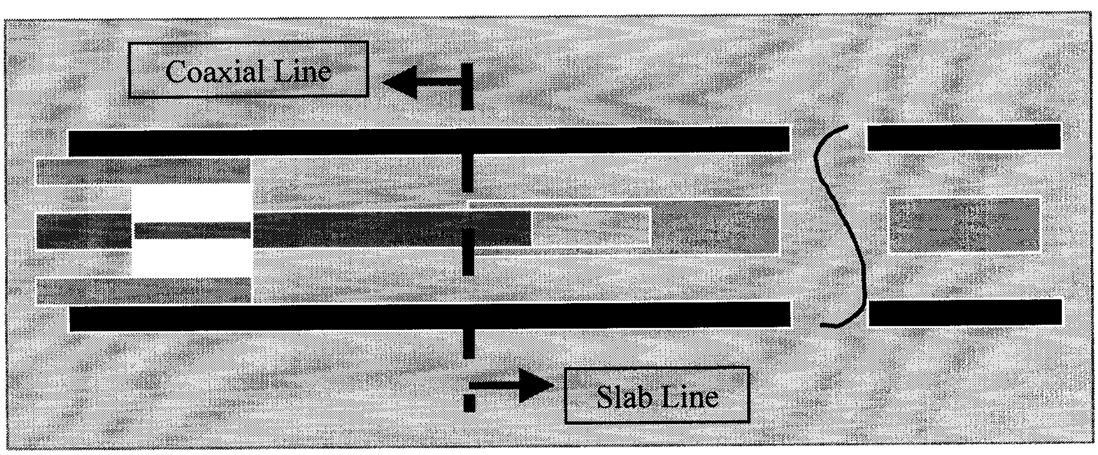

Figure 6.8 DMT Transmission Phase Adjustment Design

6.5 DIFFERENTIAL TEST FIXTURE

The Differential Test Fixture is designed to hold and bias the DUT. Since the differential device has two input and two output leads, two 50-Ohm transmission lines are designed on the test fixture. In order to avoid possible oscillations of the DUT, the bias circuit is also designed on the test fixture.

First of all the simulation is performed using ADS. The simulation circuit includes half test fixture, and another half of fixture is identical. The complete layout is shown in figure 6.13 and 6.14, and the prototype is shown in figure 6.15.

The figure 6.16 demonstrates how the fixture is used to hold differential device.

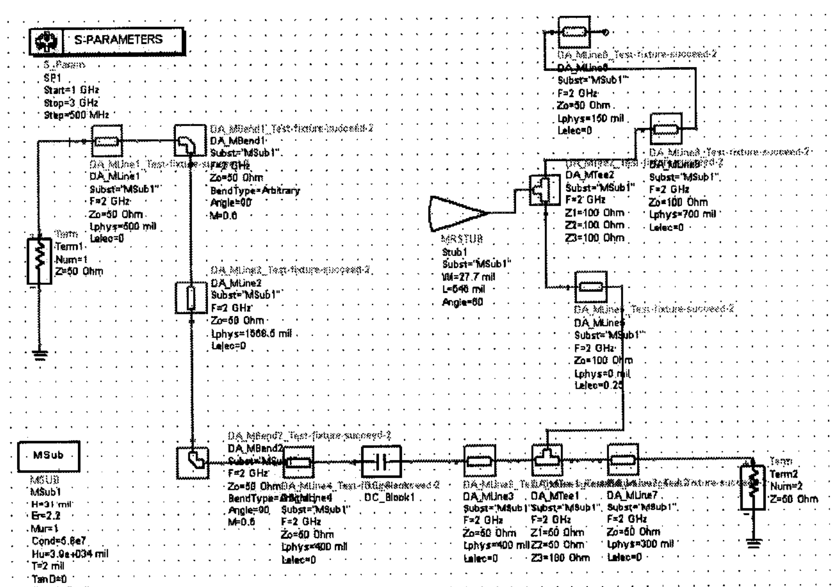

Figure 6.9 Differential Test Fixture Design Circuit

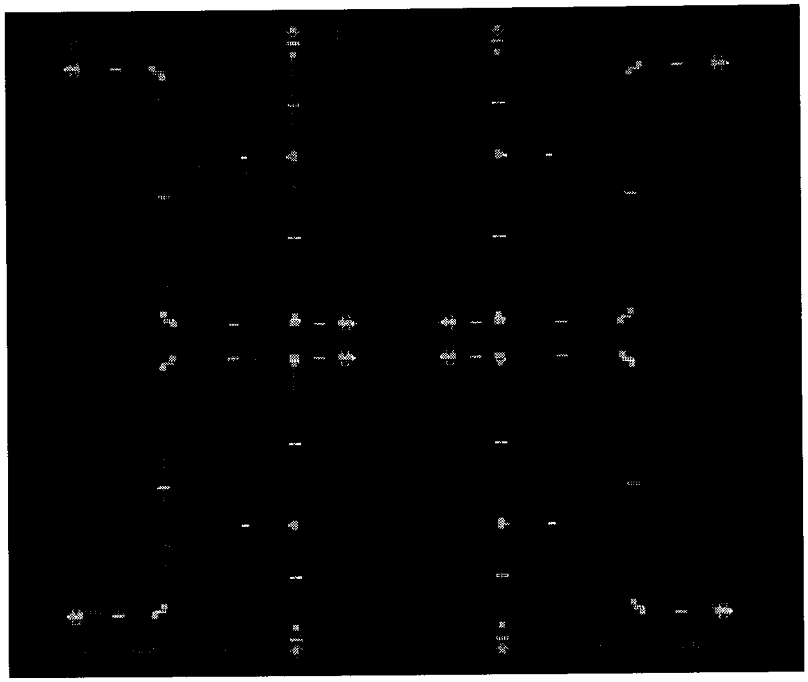

Figure 6.10 Differential Test Fixture Design Layout

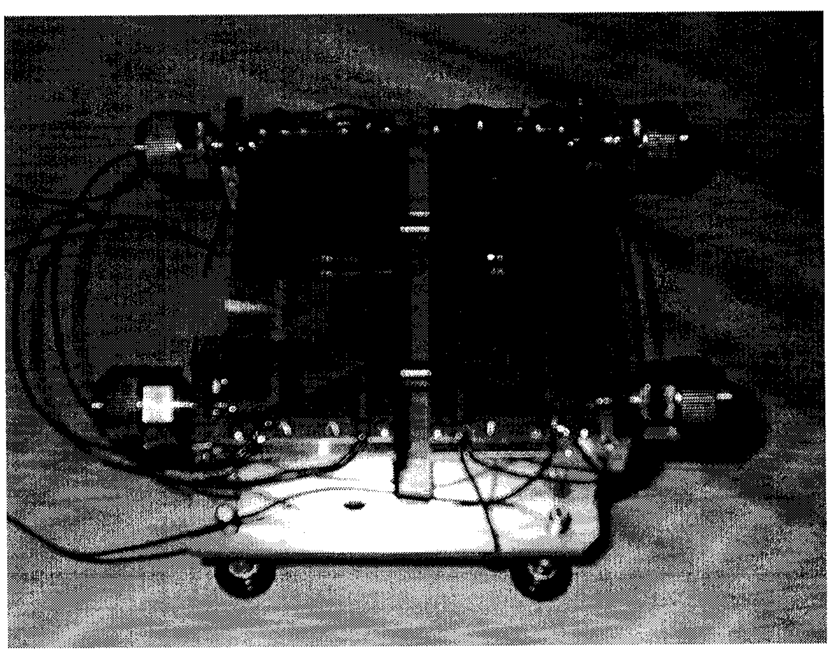

Figure 6.11 Differential Test Fixture Real Circuit

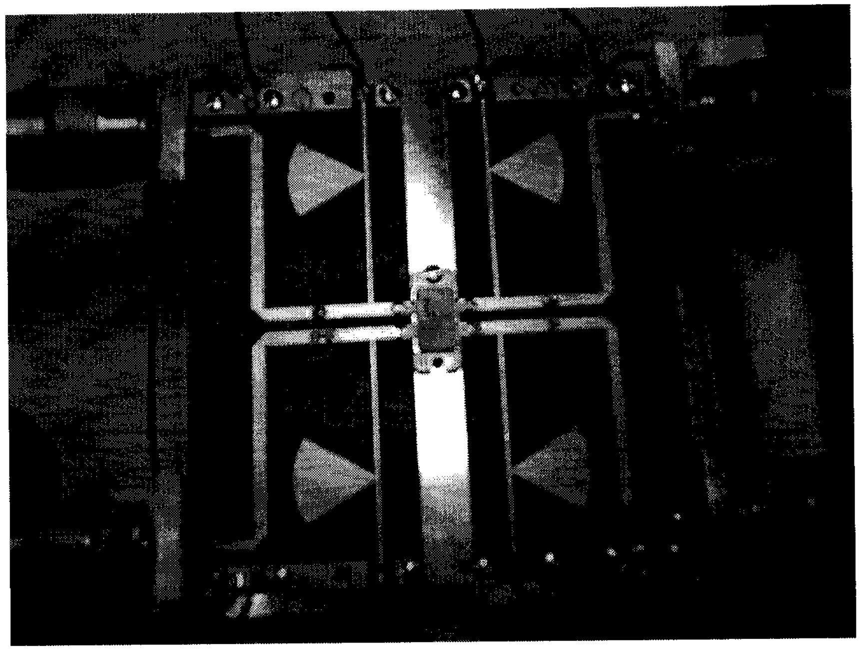

Figure 6.12 Differential Test Fixture Real Circuit with Device

6.6 CONCLUSION

Differential Microwave Tuners are the key elements in differential load pull measurements. A device is measured at different differential impedances, which are generated by the differential tuner. A Differential Test Fixture is used to hold and connect the differential device to the differential tuners.

CHAPTER 7
MICROWAVE BALUNS

7.1 INTRODUCTION

Balun-transformers provide the key to differential amplifier design. Without balun-transformers the minimum device impedance (real) that can be matched to 50 ohms with acceptable bandwidth and loss is approximately 0.5 ohms. The key to increasing the transistors' output power is reducing this impedance ratio. Although 3 dB hybrid combiners can double the maximum power output, they lower the matching ratio to only 50:1.

In this project the baluns provide differential signal at input of the DUT, and then convert differential signal to single-ended signal, which can be measured by single-ended instruments directly.

7.2 BALUN STRUCTURE

There are many types of baluns, [14], [15], [19], [34], [38], from coaxial structure to micro-strip planar structure, from couple line structure to ferrite wire structure. The commercial available chip baluns are adopted in this project.

According to traditional unbalanced port definition, the balun is actually a three-port device shown in figure 7.1, with 50-ohm impedance at one port and 25-ohm impedance at the other two ports.

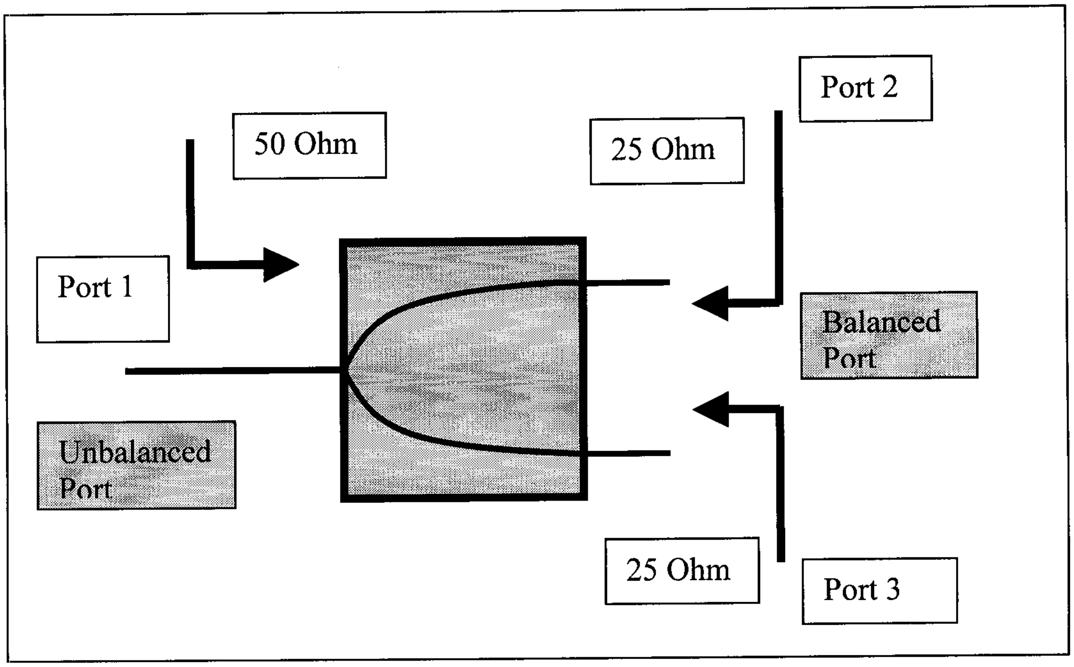

Figure 7.1 Balun Structure

7.3 BALUN APPLICATION

Balun application [14] in the differential mode measurement is explained in figure 7.2. It becomes very important to find a way to characterize the balun and integrate it into the differential load pull system. Actually two baluns are needed in the system; one is at input to split the power and another one at the output to combine the power.

From a characterization point of the view, the balun can actually be treated as a three-port device. Port 1 is the signal-ended port where there is only common mode signal.

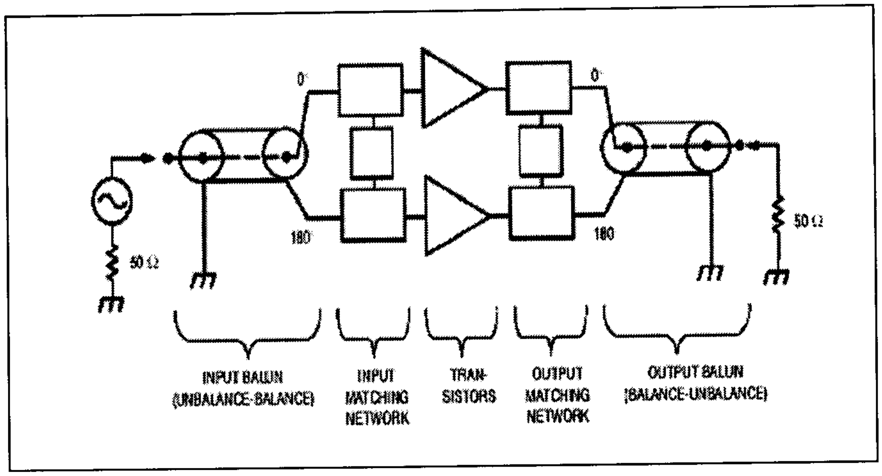

Figure 7.2 Balun Application [14]

7.4 WIDE BAND TRNSFORMER DESIGN

25-Ohm impedance of the balun is needed to transform to 50 Ohm [21] so that tuner can cover all whole Smith Chart. In order to cover wide band frequency, the multi-section transformer is designed and simulated in ADS.

7.4.1 SIMULATION CIRCUIT

As shown in the figure 7.3, the transformer is designed and the sub-circuit is shown in figure 7.4.

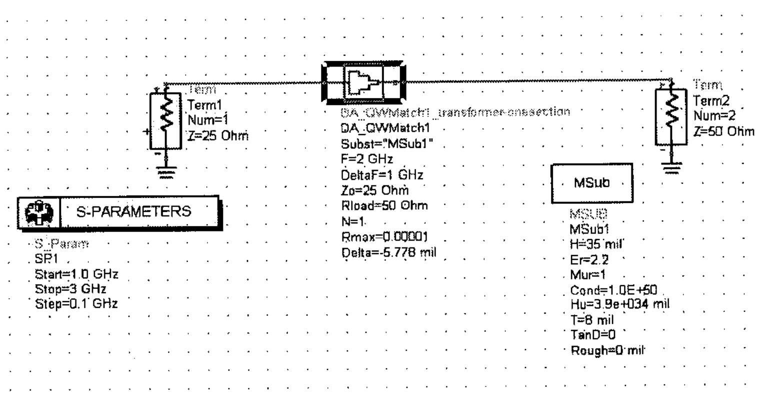

Figure 7.3 Transformer Simulation Circuit in ADS

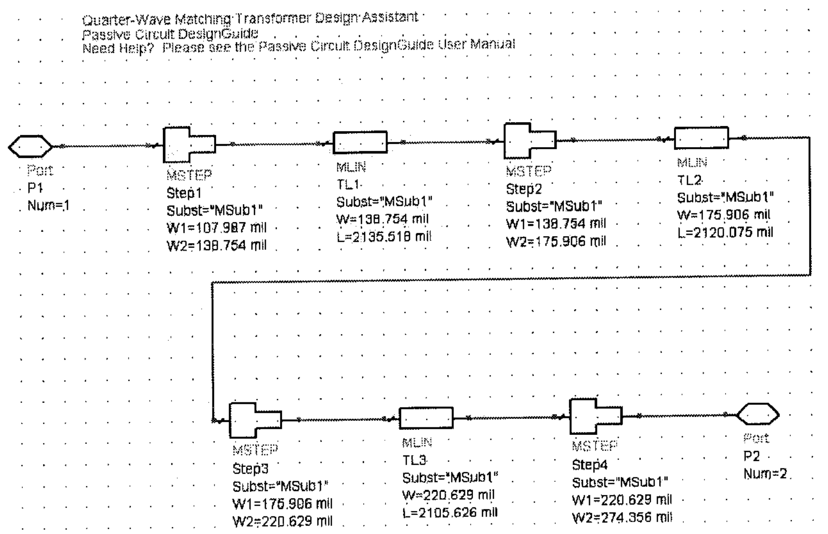

Figure 7.4 Multi-Section Transformer Simulation Circuit

7.4.2 SIMULATION RESULT

The simulation result shows that the balun transition board can be used at 1 GHz to 3 GHz frequency range.

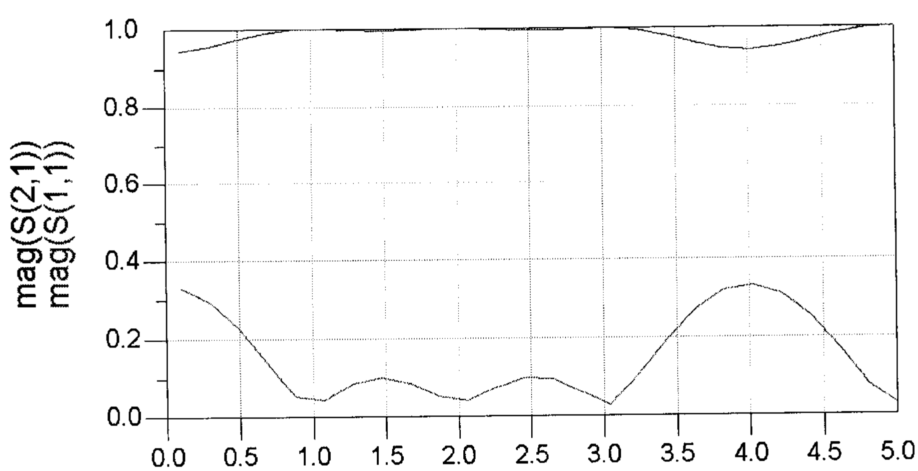

Figure 7.5 Multi-Section Transformer Simulation Result

7.4.3 COMPLET CIRCUIT

This complete circuit includes additional 50-Ohm transmission lines, which are designed to fit the dimension of the DMT.

The simulation circuit, simulation results, complete layout as well as the prototype are shown in figure 7.6, 7.7,7.8 and 7.9.

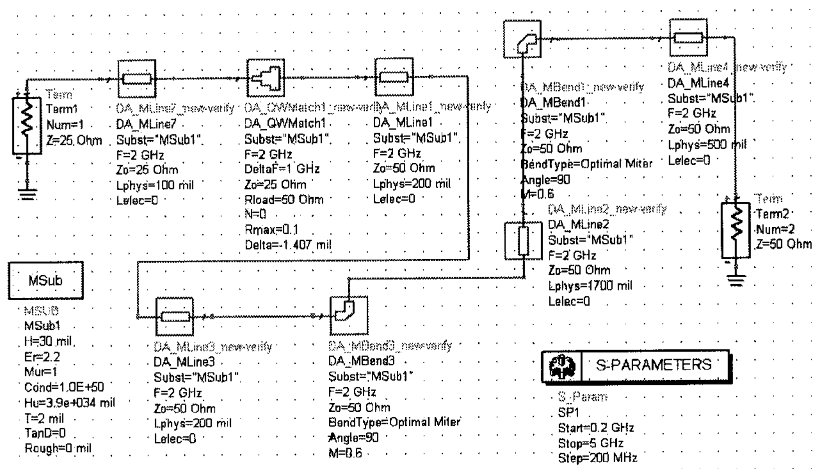

Figure 7.6 Multi-Section Transformer Complete Circuit Simulation

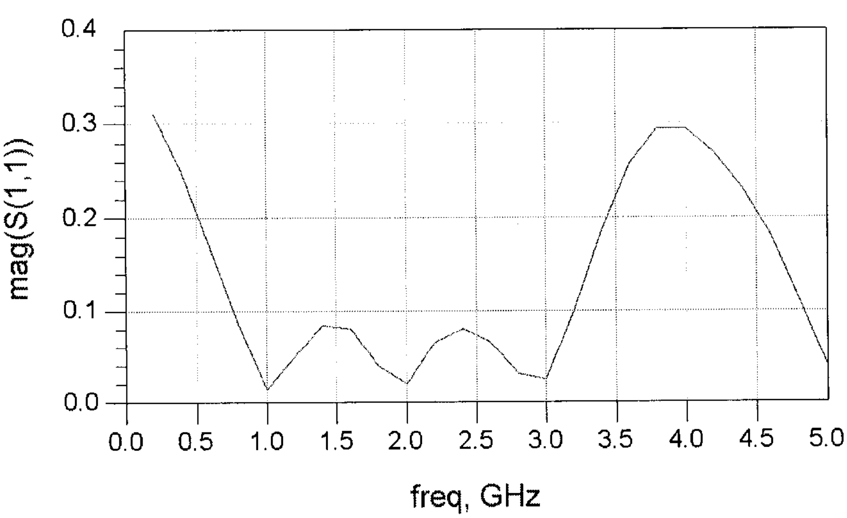

Figure 7.7 Multi-Section Transformer Simulation Result

7.4.4 COMLETE LAYOUT

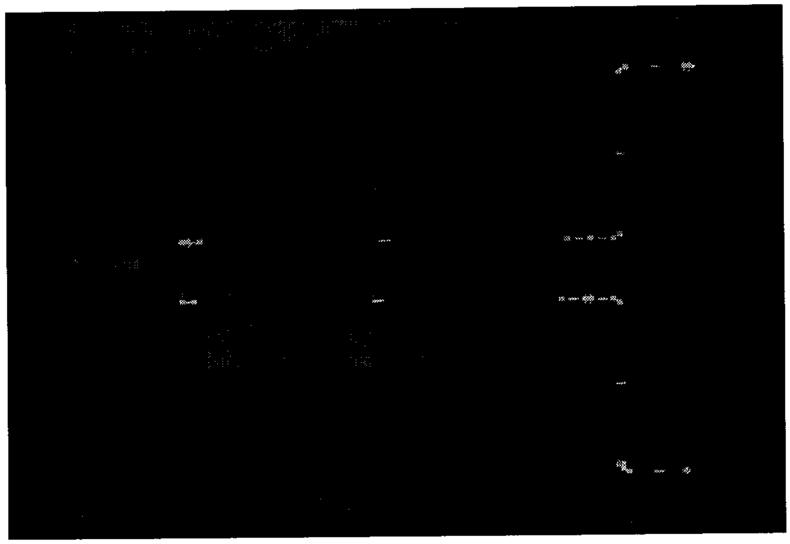

Figure 7.7 Multi-Section Transformer Complete Layout

7.4.5 REAL BALUN TRANSITION BOARD

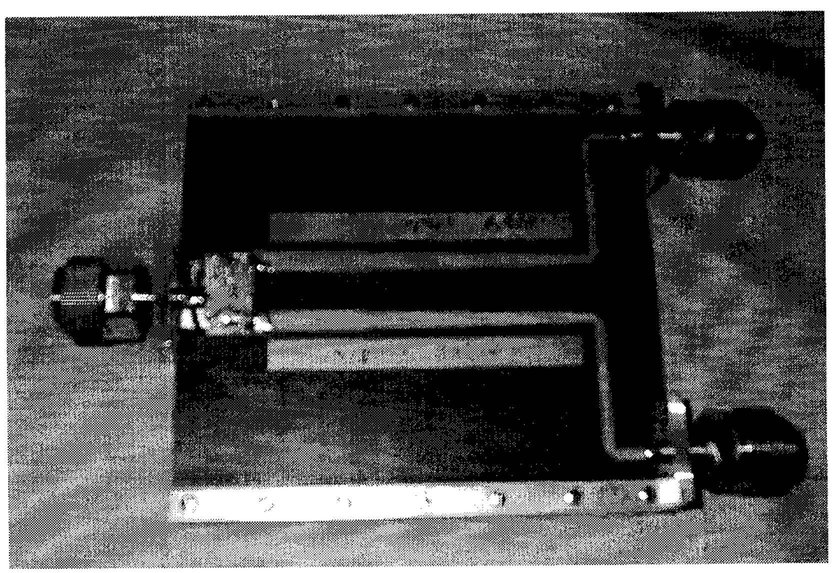

Figure 7.8 Balun transition board

7.5 BALUN CHARACTERIZATION

The Mixed Mode S-parameters of baluns are needed for system computation. Once we get the S_{ss11}, S_{ds21}, S_{ds12}, S_{dd22}, the available loss can be calculated and used for input power de-embedding. And the power loss is calculated and used for the output power de-embedding.

7.5.1 DEVICE SELECTION

In this project, chip baluns from Anaren are chosen. First of all the chip baluns are soldered on transition board. Each port of the balanced output is 25 ohm, which is converted to 50 ohms using a micro strip transformer. Three ports single ended S-parameters are measured and transformed to mixed mode S-parameters by applying formula in chapter 3.

7.5.2 CHARACTERIZATION PROCEDURE

First of all several symbols are defined as the following.

Input Balun: Output Balun 50 Ohm load

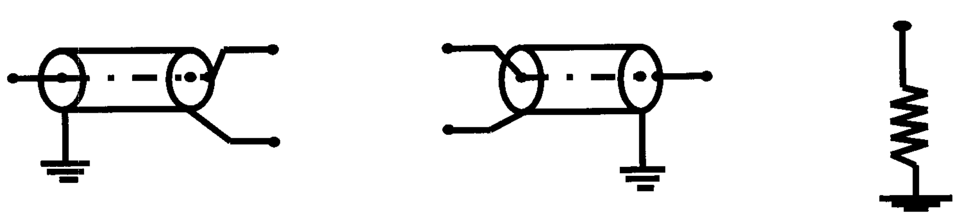

Figure 7.9 Some Symbols

The two-port single-ended S-parameters are measured, while a high-precision 50-Ohm load terminates the other port. Three standard two-port S-parameters measurement are needed to fully characterize a balun.

Step 1. Measure standard S-parameters from port 1 to port 2 while port 3 is terminated by precision 50-Ohm load, shown in figure 710. One set of S-parameters will be saved, named as p12.s2p for instance.

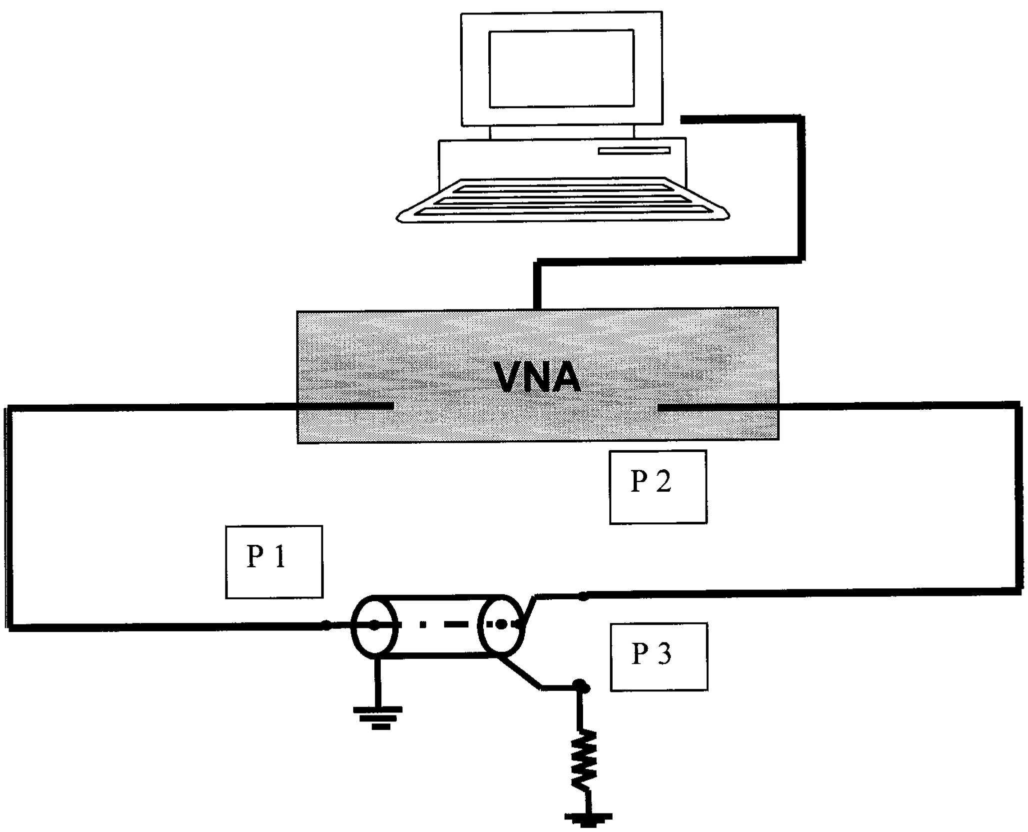

Figure 7.10 Balun Characterization -1

Step 2. Measure standard S-parameters from port 1 to port 3, while a high precision 50-Ohm load terminates port 2, shown in figure 7.10. Second sets of S-parameters are saved in file p13.s2p.

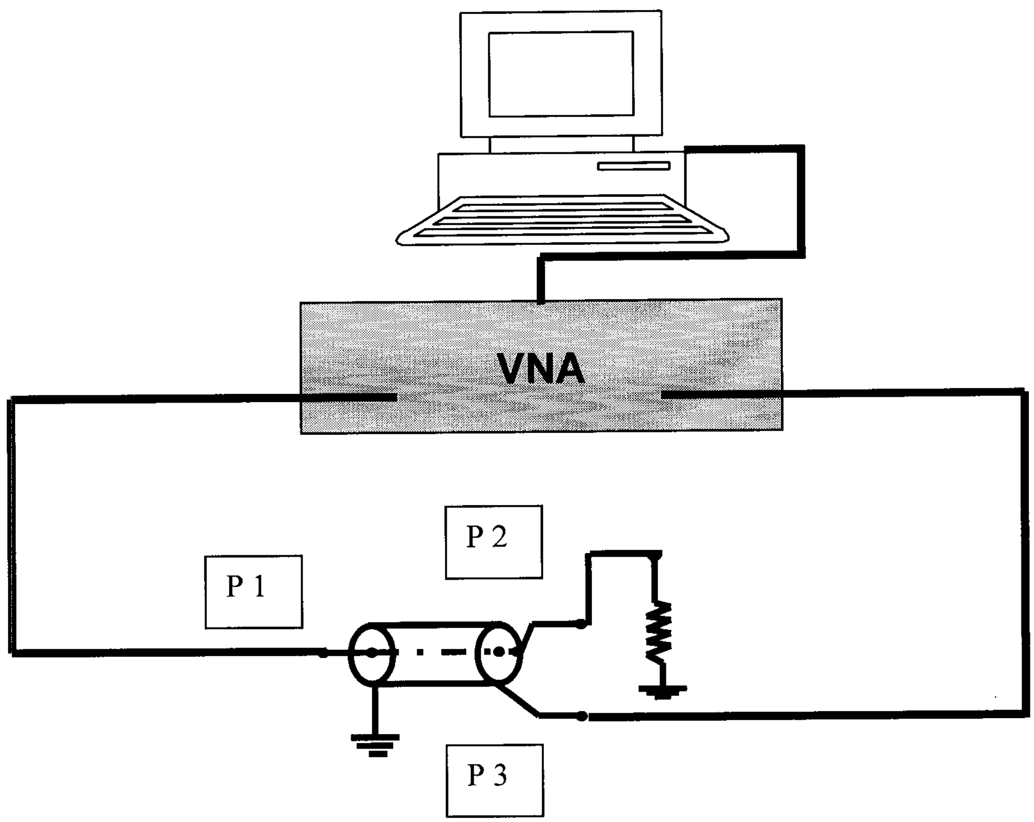

Figure 7.11 Balun Characterization -2

Step 3. Measure standard S-parameters from port 2 to port 3, while the port 1 is terminated by high precision 50-Ohm load. The third sets of S-parameters are saved in file p23.2p.

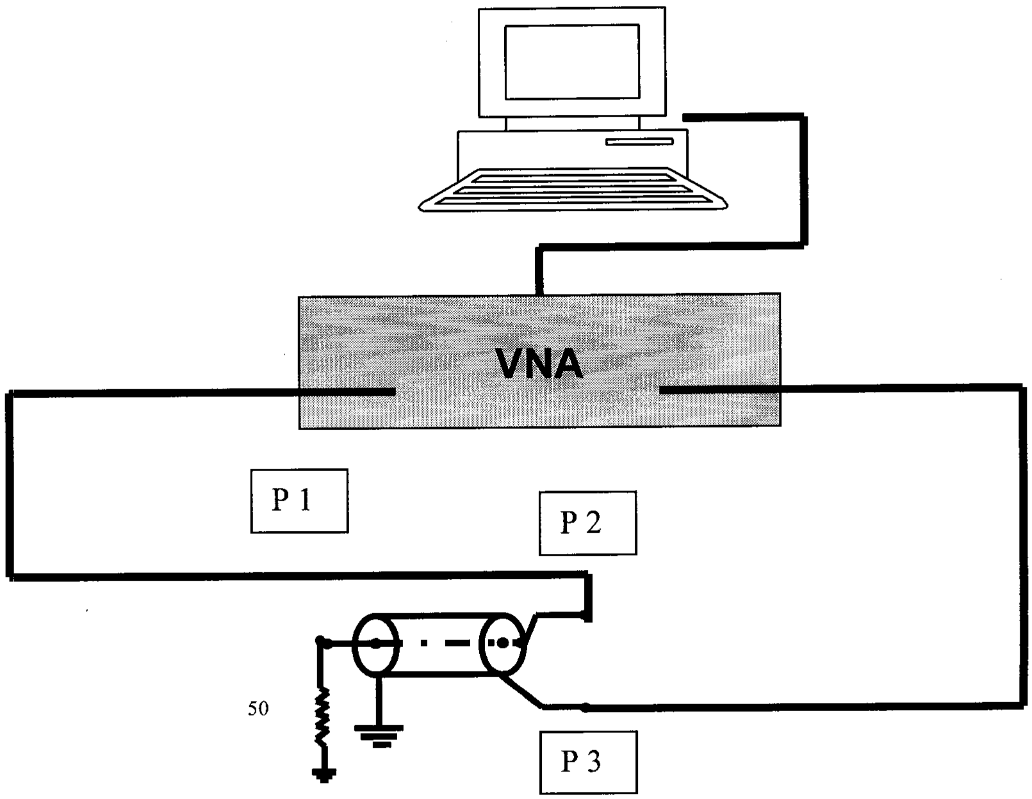

Figure 7.12 Balun Characterization -3

Step 4. Calculate mixed mode S-parameters. Actually only the differential mode S-parameters are computed from the three S-parameter files measured in step 1,2 and 3.

Finally the differential S-parameters are saved as standard Focus S-parameters files with format S11, S21, S12, S22. Notice that s11 is single ended S-parameter, s22 is differential mode port 2 reflection factor, s12 is reverse transmission, and s21 is forward transmission in differential mode.

7.6 CONCLUSION

A balun can be characterized as a three-port device rather than two port differential device. The three-port single-ended S-parameters are then transformed into mixed mode S-parameters.

CHAPTER 8
SYSTEM CALIBRATION

8.1 INTRODUCTION

All the components used in the setup should be pre-calibrated. Since S-parameters and mixed mode S-parameters are adopted to calibrate the setup, a VNA is used to measure S-parameters of all components including the DMT tuners.

8.2 SETUP REVIEW

Let us review the differential load pull setup first. For a differential load pull system, the baluns should be placed before the input tuner and after the output tuner. Of course tuners and test fixture must be differential tuners and differential test fixture.

A typical Load Pull Setup includes:

a) Setup Hardware
   - Two Differential Microwave Tuners at Frequency f_0
   - One Differential Test Fixture (or wafer-probe station with differential probes)
   - One or two Directional Couplers
   - One or two isolators
   - A Power Combiner (for Intermod measurements)

- One or two Driver Amplifiers (two, for Intermod)
- Two balun transition Boards
- A set of adapters, cables, etc.
- One control PC with GPIB interface and tuner controller card

b) Measurement Instruments

- Dual Channel (or two single channel) Power Meter(s)
- One (or two - for Intermod) Signal Sources
- One Power Supply (more for testing multistage amplifiers)
- Spectrum Analyzer (for ACPR, Intermod, ICP3, etc.)

c) Optional/Temporarily used Instruments

- Vector Network Analyzer
- Digital Multimeters (for PAE measurements w/o programmable power supply)
- Digital Thermometer (for Temperature control and monitoring)

The diagram of the setup and a picture of the real setup are shown in figure 8.1 and figure 8.2.

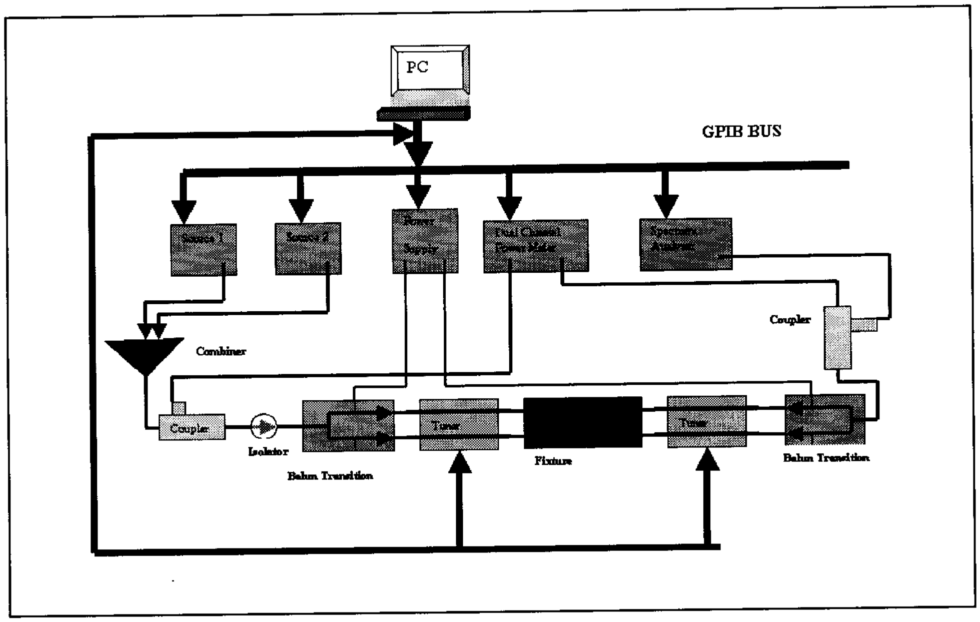

Figure 8.1 DLP Configurations

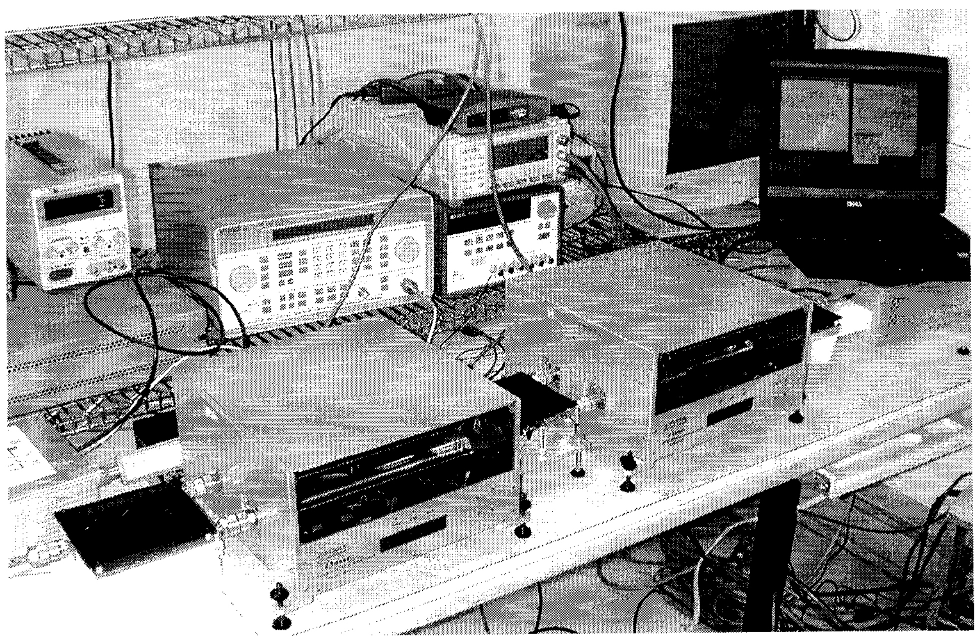

Figure 8.2 DLPS Practical Setup

The input unbalanced signal is converted to a differential signal that is injected into the differential device through differential tuner and differential test fixture. The signal, amplified by DUT, is delivered to the output differential test fixture and differential tuner. Finally the signal is transformed by output balun to an unbalanced signal that can be measured directly by power meter, spectrum analyzer or other equipments.

8.3 VNA CALIBRATION

The network analyzer must be carefully calibrated prior to performing the tuner and setup calibration. Since all other calibrations and measurements depend on the quality of the VNA calibration, it is important to ensure accurate VNA calibration.

The VNA should be calibrated using a TRL/LRM technique. The VNA must be calibrated for the same frequencies at which the tuners and setup are to be calibrated. The Differential Load Pull system shall not use interpolated data of the VNA. The VNA calibration should be verified with through line, short, and offset short tests. The through line return loss should be less than 40 dB, and the ripple should be less than 0.1 dB up to 18 GHz.

8.4 COMPONENT CALIBRATION

Component calibration is actually S-parameter measurement using a VNA, all the data are saved in the computer file.

8.4.1 S-PARAMETERS MEASUREMENT

S-parameters measurements are performed using a Vector Network Analyzer (VNA) connected via an IEEE-488 interface bus to the computer. An IEEE-488 interface card must be installed in order to perform S-parameter measurements.

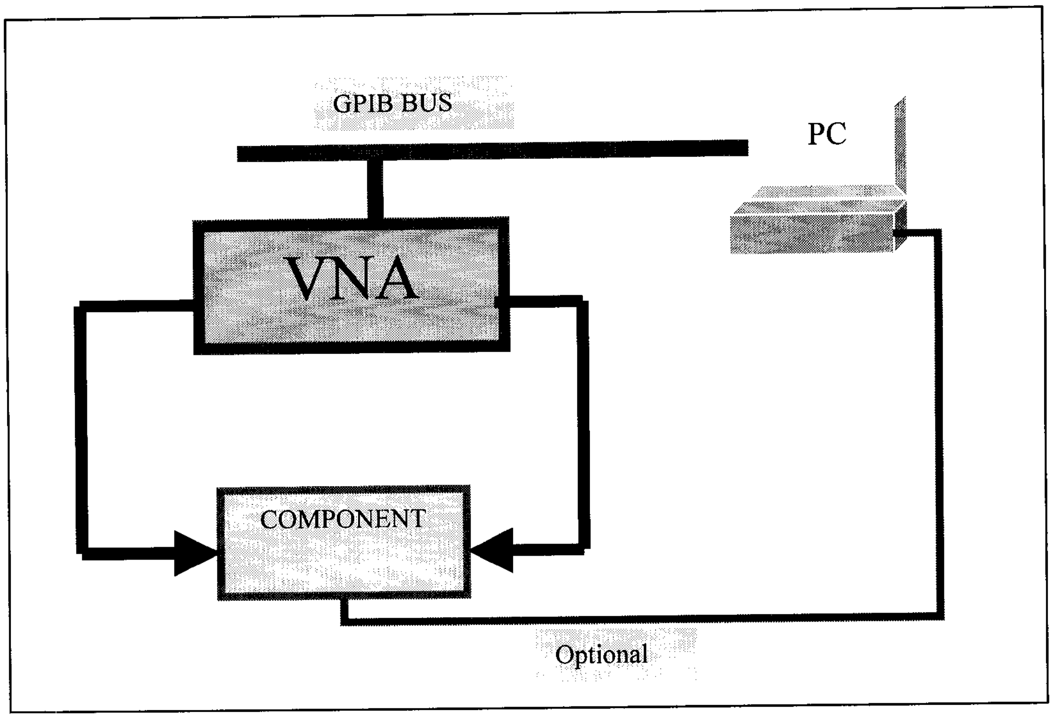

Figure 8.3 S-parameters Measurement

For all S-parameter measurements, software uses the frequency range definitions of the network analyzer and the currently activated calibration kit. During the network analyzer calibration, use frequency lists that only include the frequency points at which measurements are going to be performed. If measurements need to be performed at a specific frequency, it is essential that this frequency be included in the S-parameter file (VNA calibration).

8.4.2 INPUT BLOCK

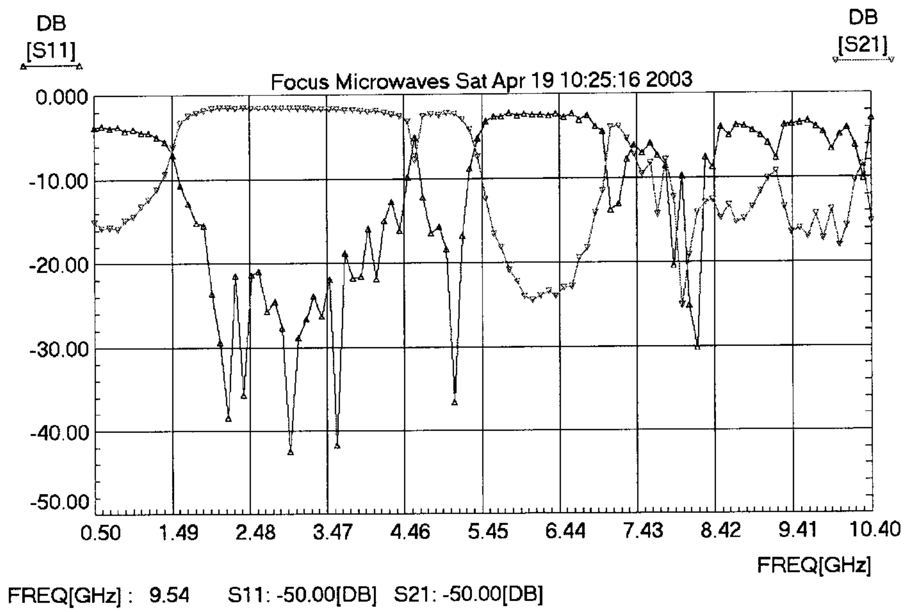

Figure 8.4 S-parameters of Input Section

8.4.3 OUTPUT BLOCK

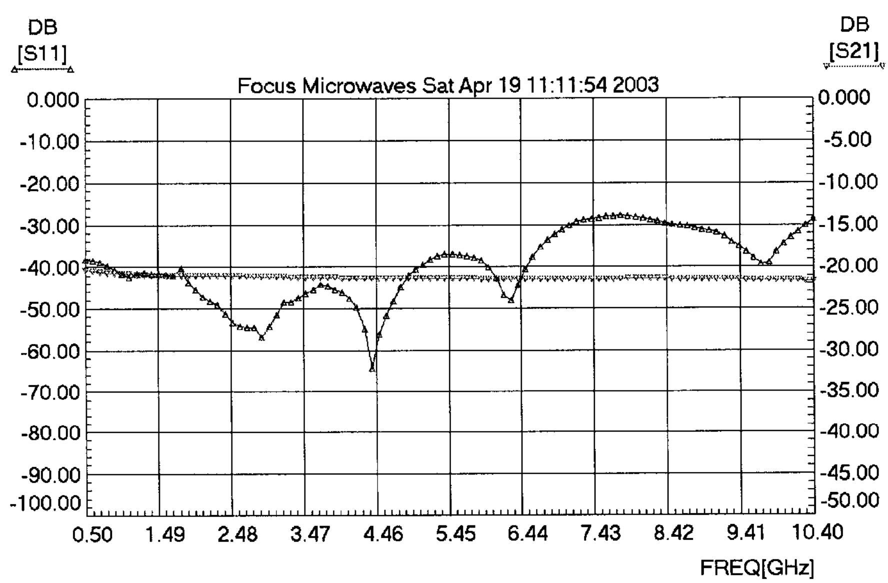

Figure 8.5 S-parameters of output Section

8.4.4 INPUT COUPLING

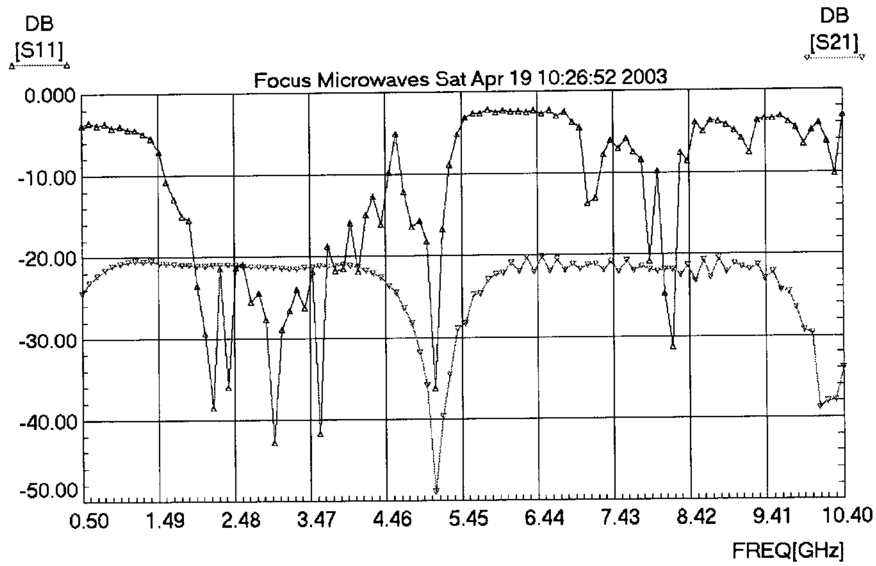

Figure 8.6 S-parameter of Input Coupling

8.4.5 INPUT BALUN PORT 1-2

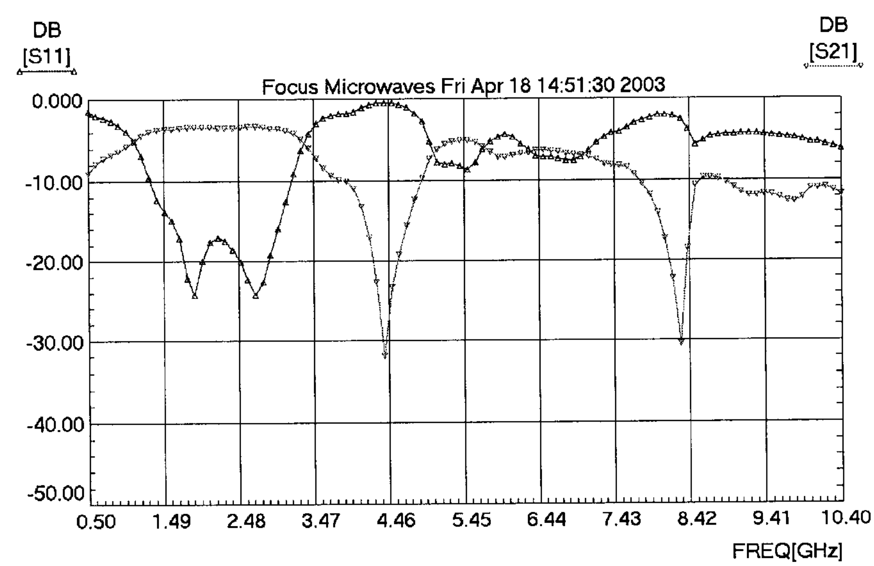

Figure 8.7 S-parameter of Input Balun Port 1-2

8.4.6 INPUT BALUN PORT 1-3

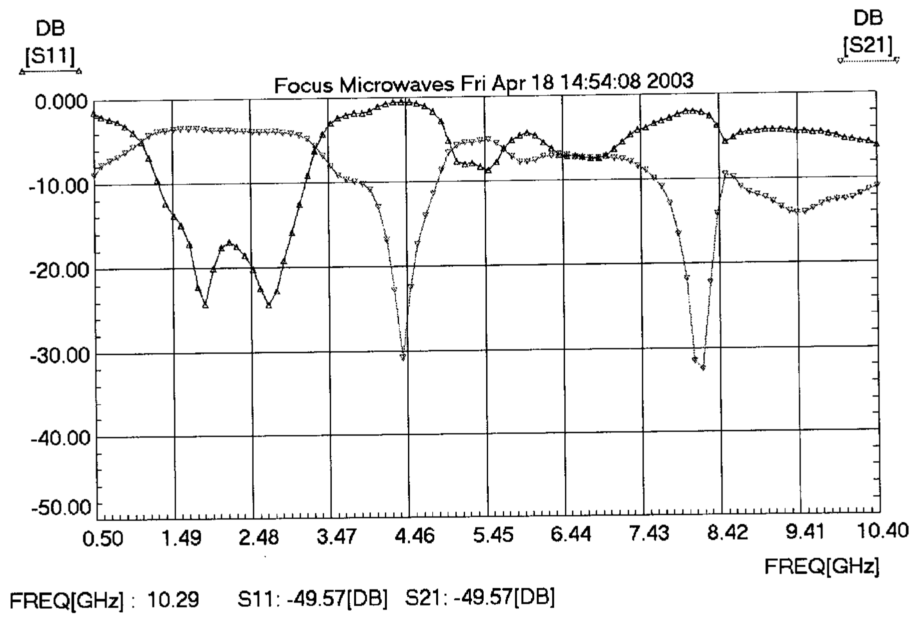

Figure 8.8 S-parameter of Input Balun Port 1-3

8.4.7 INPUT BALUN PORT 2-3

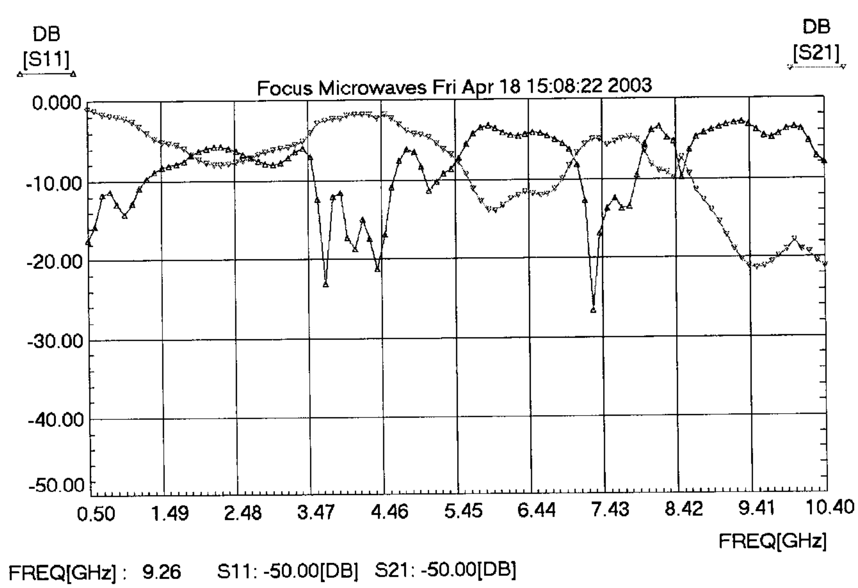

Figure 8.9 S-parameter of Input Balun Port 2-3

8.4.8 OUTPUT BALUN PORT 1-2

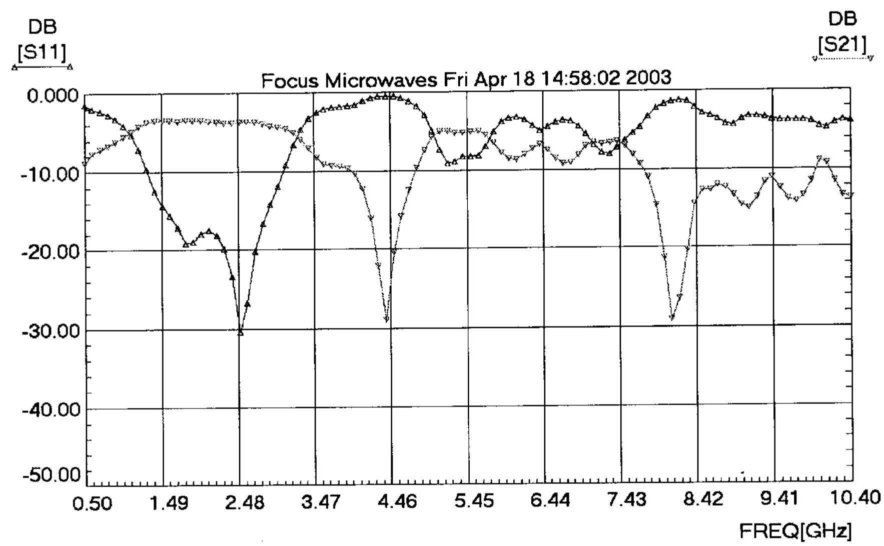

Figure 8.10 S-parameter of Output Balun Port 1-2

8.4.9 OUTPUT BALUN PORT 1-3

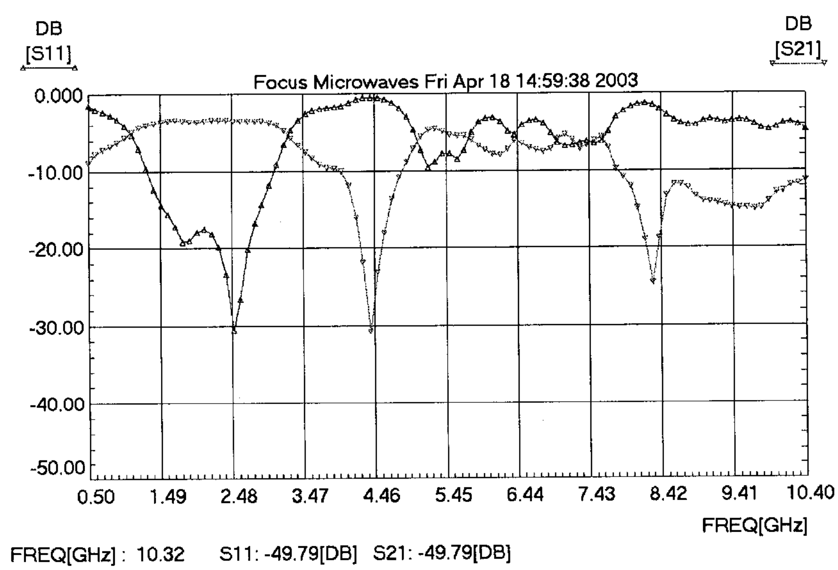

Figure 8.11 S-parameter of Output Balun Port 1-3

8.4.10 OUTPUT BALUN PORT 2-3

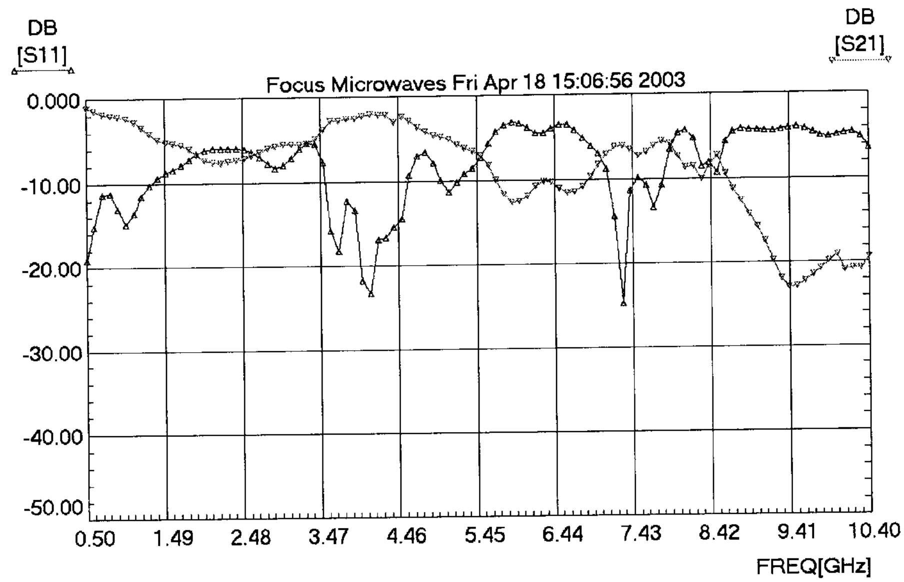

Figure 8.12 S-parameter of Output Balun Port 2-3

8.5 DIFFERETIAL TEST FIXTURE CALIBRATION

8.5.1 TRL MEASUREMENT TECHNIQUE

To measure and characterize a differential test fixture the through-reflect-line (TRL) technique is used to extract S-parameters of two parts of the test fixture [11], [22].

Like other calibration methods, the TRL introduces a 12-term error correction vector for each frequency point. To calculate these terms standards for which *S*-parameters are known must be measured. These standards include a short or open, a through and a delay line with known electrical delay. The TRL calibration corrects phase and magnitude errors introduced by the sliding of reference planes and the insertion loss of cables, fixtures and connectors. Precision calibration standards should be used because each defect in a standard will be transferred into calibration errors.

Two popular correction vectors are the eight term and 12-term correction vectors.

8.5.1.1 THE 12 TERMS ERROR CORRECTION

Twelve-term error correction permits the correction of six terms in forward and six in reverse mode. These six terms are:

- ED, the directivity term
- ER, the reflection tracking term
- EL, the load match term
- ET, the transmission tracking term
- ES, the source match term
- EX, the isolation term

These are seen in the flow graph (Figure 8.13), which represents the forward error terms. This correction is the most efficient, is available on high quality network analyzers and it corrects all systematic errors by the network analyzer. The eight-term calibration is often used in less expensive network analyzers. It is simpler but does not correct all the systematic errors, such as the errors introduced when switching to an alternate measurement direction.

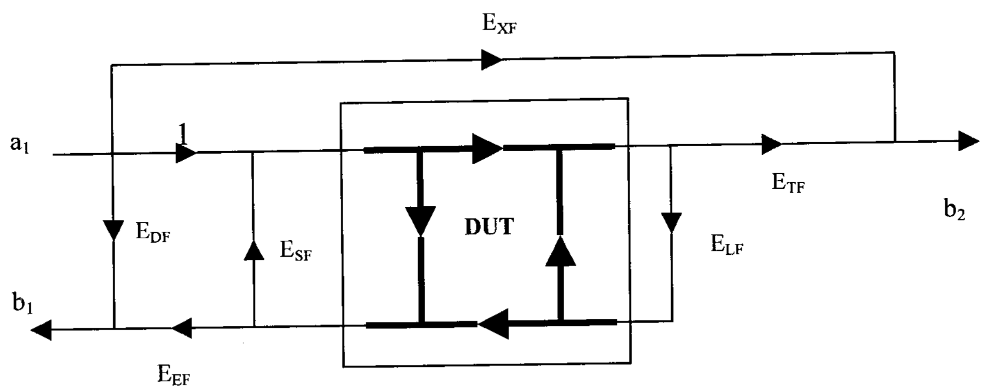

Figure 8.13 Flow graph of the forward path 12-term error correction.

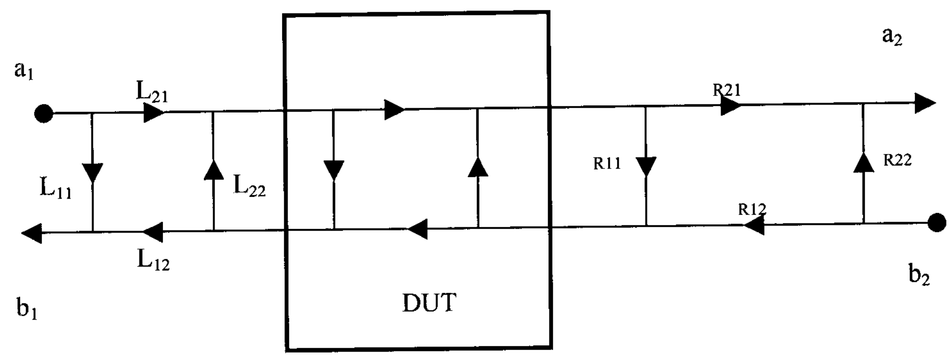

Figure 8.14 Eight Terms Correction

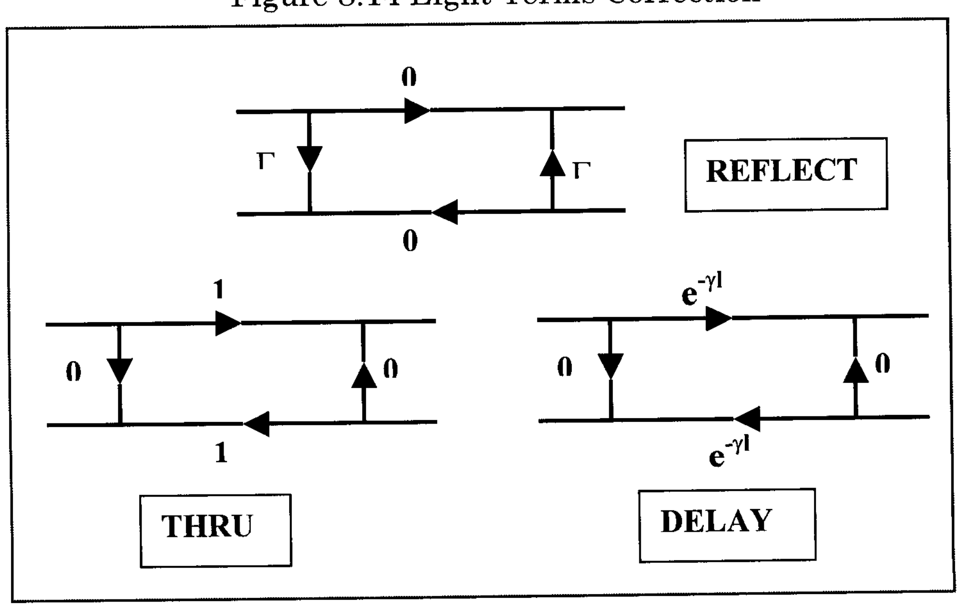

Figure8.15 TRL standards

8.5.1.2 EIGHT TERM CORRECTION

The eight-term error correction models are each accessed by a quadripole defined by its S-parameters. There are four terms per port and two ports. In some applications isolation is also corrected. This is not included in the eight-term correction. This kind of correction can be modeled by the flow graph (Figure 8.14).

8.5.1.3 TRL CALIBRATION

Using a system of equations after measuring three standards, it is possible to find 10 of the 12 error terms. The two missing terms are the forward and reverse isolation terms. These cannot be extracted from that set of equations. If the user wants to calibrate these parameters, isolation calibration with two loads (as in the OSLT calibration) is necessary. The flow graph of each TRL standard is shown in Figure 8.15.

8.5.2 CALIBRATION OF TEST FIXTURE

Before the mathematical process of de-embedding is developed, the test fixture and the DUT must be represented in a convenient form. Using signal flow graphs, the fixture and device can be represented as three separate two-port networks (Figure 8.16).

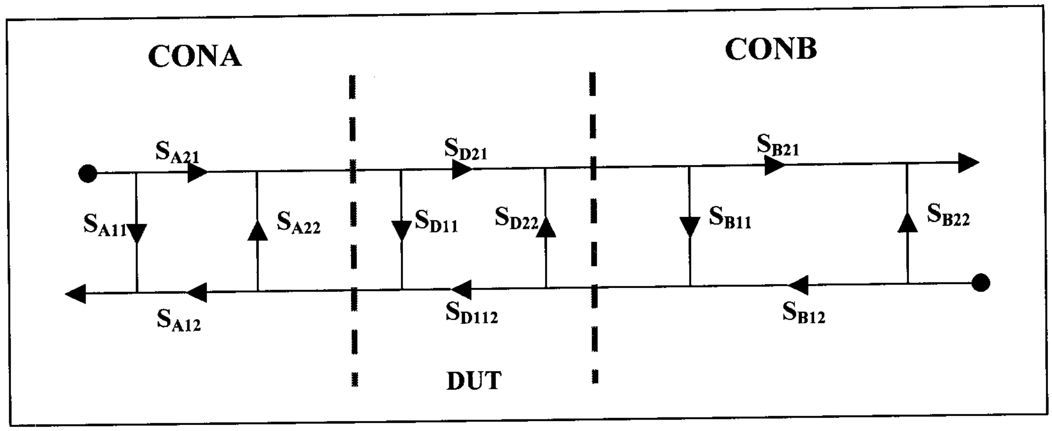

Figure 8.16 Test fixture With Device Under Test

The test fixture is divided in half to represent the coaxial to micro-strip interfaces on each side of the DUT. The two fixture halves will be designated as CONA and CONB for the left-hand and right-hand sides of the fixture respectively. The S-parameters $S_A$xx (xx = 11, 21, 12, 22) will be used to represent the S-parameters for the left half of the test fixture and $S_B$xx will be used to represent the right half.

The two-port T-parameter matrix can be represented as [T], where [T] is defined as having the four parameters of the network. Because we defined the test fixture and DUT as three cascaded networks, we can easily multiply their respective T-parameter networks, T_A, TDUT and T_B.

$$\left[T_{MEASURED}\right]=\left[T_{A}\right]\left[T_{DUT}\right]\left[T_{B}\right] \tag{8.1}$$

It is only through the use of T-parameters that this matrix equation be written in this simple a form. This matrix operation will represent the T-parameters of the test fixture and DUT when measured by the VNA at the measurement plane.

General matrix theory states that the matrix determinate is not equal to zero, then the matrix has an inverse. Any matrix multiplied by its inverse will result in the identity matrix. For example, if we multiply the following T-parameter matrix by its inverse matrix, we obtain the identity matrix.

$$[T][T]^{-1} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{8.2}$$

It is our goal to de-embed the two sides of the fixture, TA and TB, and gather the information from the DUT or T_{DUT}. Extending this matrix inversion to the case of the cascaded fixture and DUT matrices, we can multiply each side of the measured result by the inverse T-parameter matrix of the fixture and yield the T-parameter for the DUT only.

$$[T_A]^{-1}[T_A][T_{DUT}][T_B][T_B]^{-1} = [T_{DUT}] \tag{8.3}$$

The T-parameter matrix can then be converted back to the desired S-parameter matrix using the equations.

Using the S or T-parameter model of the test fixture and VNA measurements of the total combination of the fixture and DUT, we can apply the above matrix equation to deembed the fixture from the measurement.

8.5.3 MEASUREMENT SETUP

The procedure consists of measuring 2-port S-parameters of a:

- THRU: the "centre ports" are connected back-to-back

• DELAY: inserting a delay line of "known" characteristic impedance

• REFL1 and REFL2: an identical reflection (open or short)

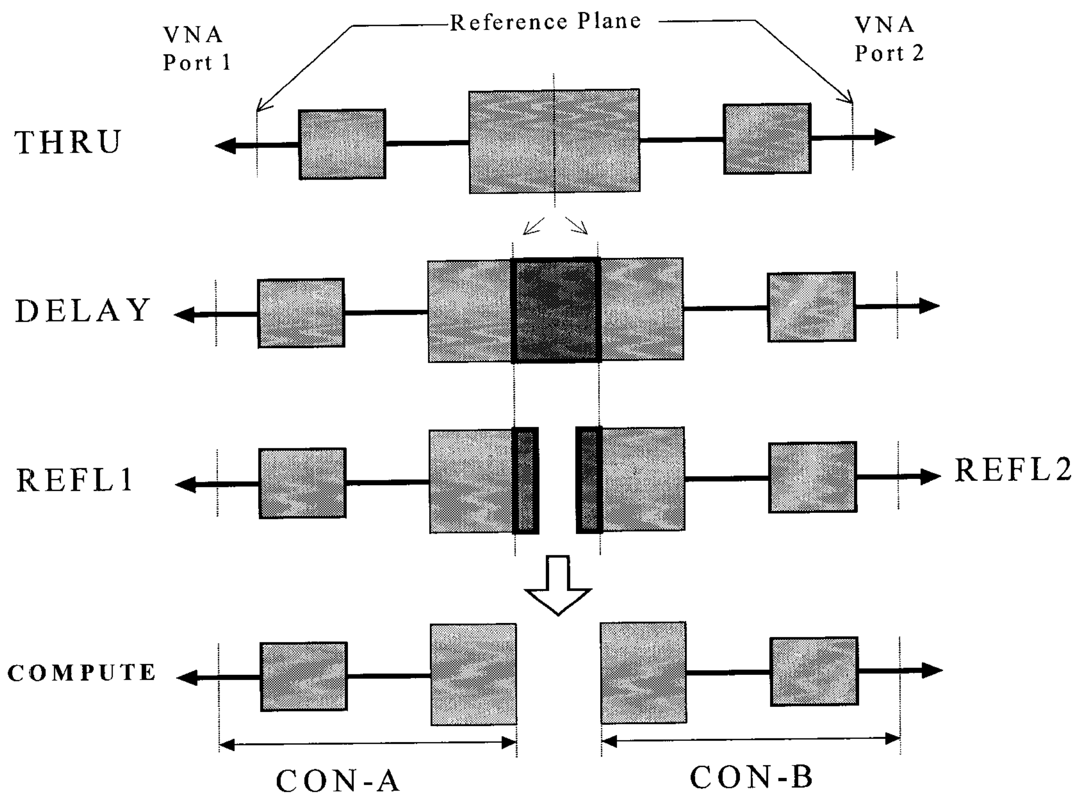

Figure 8.17 TRL Measurement

Based on these data, the program calculates the S-parameter of the input (named by default "CON-A", for "Connector A") and output (named by default "CON-B", for "Connector B") part of the setup.

The characteristic impedance of the DELAY defines the characteristic impedance of our measurement system. Calibration procedure is shown in figure 8.17. The steps are the following:

Prepare the Network Analyzer by loading the correct CAL-SET (or File). Make sure the frequencies you want to calibrate are "included" in the CAL-SET of the Network Analyzer

- THRU: Connect the two halves of the fixture together without inserting DUT.

- DELAY: Insert the Delay Line in the Fixture. Be sure you know its characteristic Impedance Z_0 (Ω). The length of the Delay Line is critical in the sense that the TRL method will compute incorrect results for frequencies where the Transmission Phase (angle of S21) of the delay is more than 180 degrees.

- REFLECT 1,2: Use the same Reflect on both Ports. In Coaxial a Short is best, in micro-strip and on-wafer use an Open.

We measure both Reflects independently. Once we get two files of input and output test fixture, we can de-embed the test fixture get the DUT S-parameters.

The steps have to be repeated since there are two transmission lines on the differential test fixture.

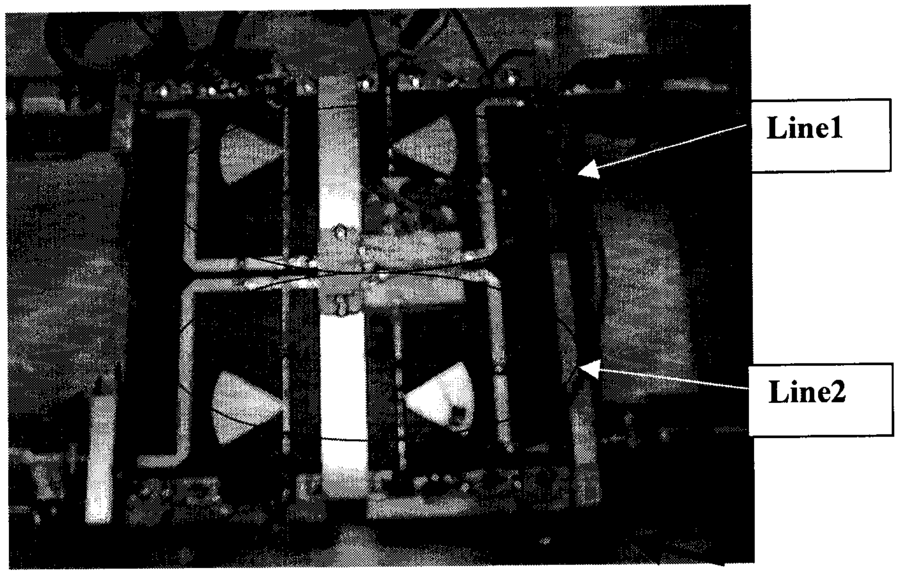

Figure 8.18 Differential Test Fixture

8.5.4 DFT LINE 1 INPUT

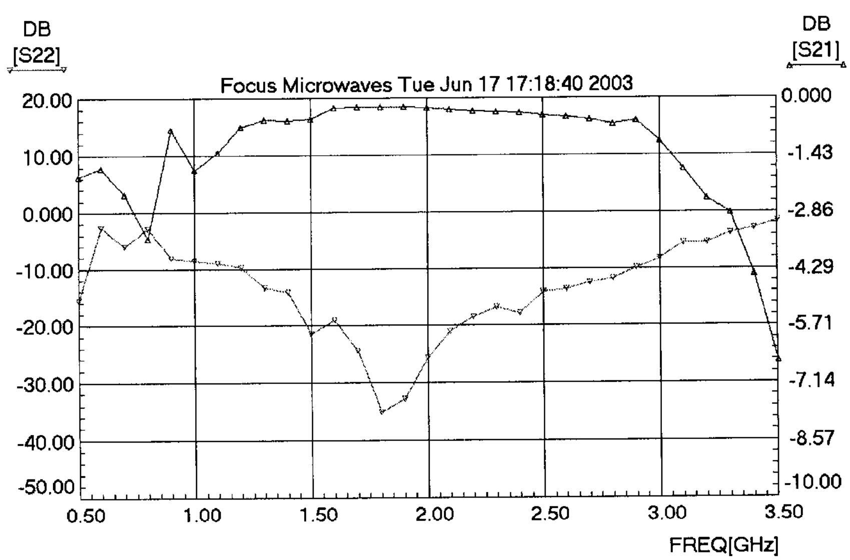

Figure 8.19 S-parameters of DTF line 1 input

8.5.5 DFT LINE 1 OUTPUT

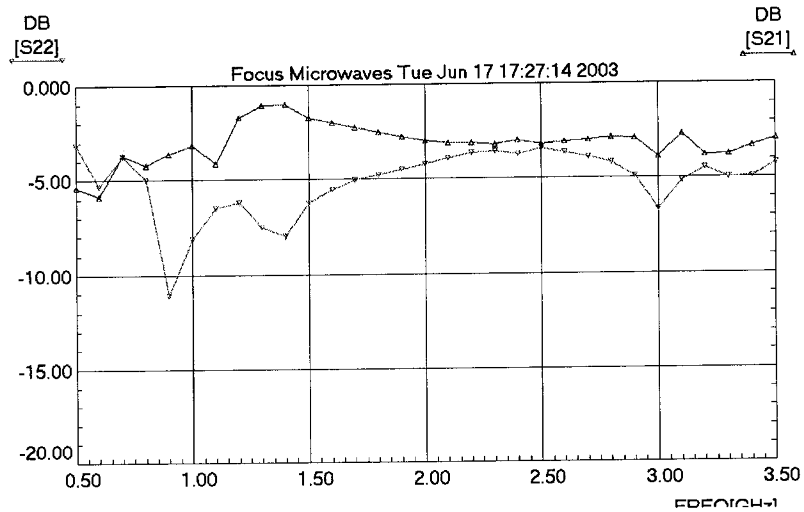

Figure 8.20 S-parameters of DTF Line 1 Output

8.5.6 DFT LINE 2 INPUT

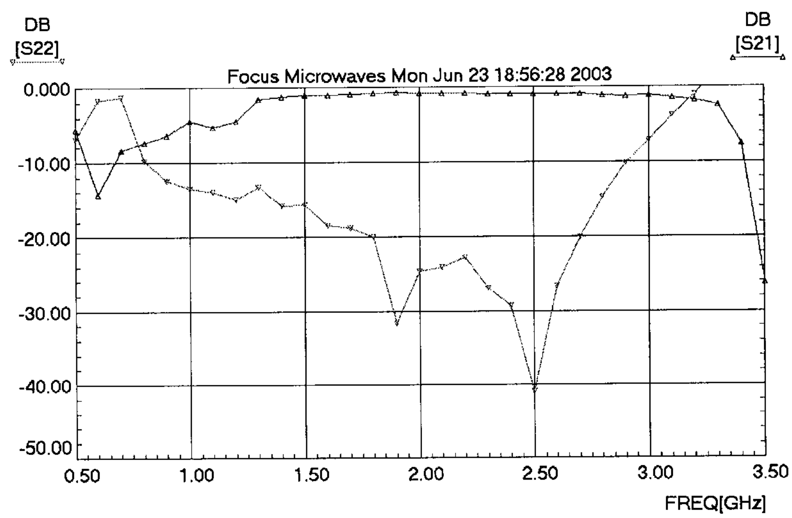

Figure 8.21 S-parameters of DTF Line 2 Input

8.5.7 DFT LINE 2 OUTPUT

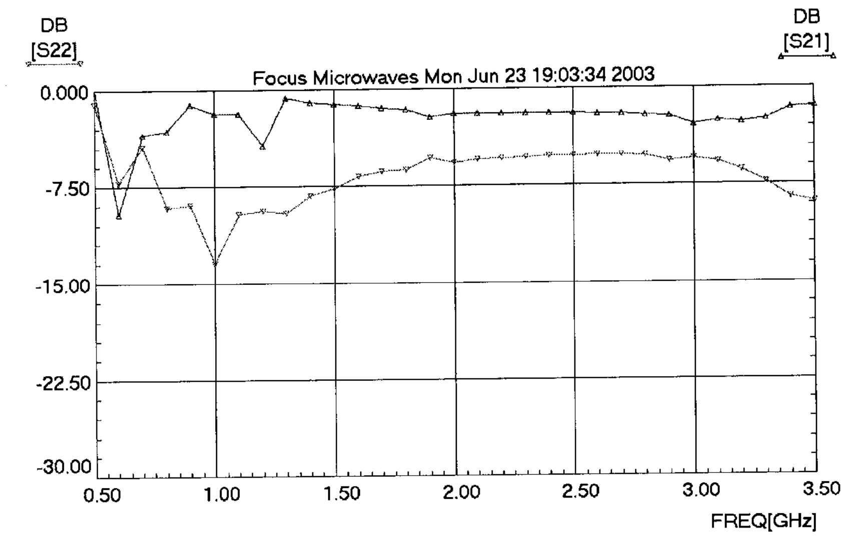

Figure 8.22 S-parameters of DTF Line 2 Output

8.6 DMT CALIBRATION

DMT tuner has two slab lines, which are completely independent. Since two lines are not coupled, calibration can be done one by one.

Software will compute mixed mode S-parameters using these two lines' S–parameters.

8.6.1 CALIBRATION SETUP

Vector network analyzer is connected to a DMT's slab-line, S parameters then are measured.

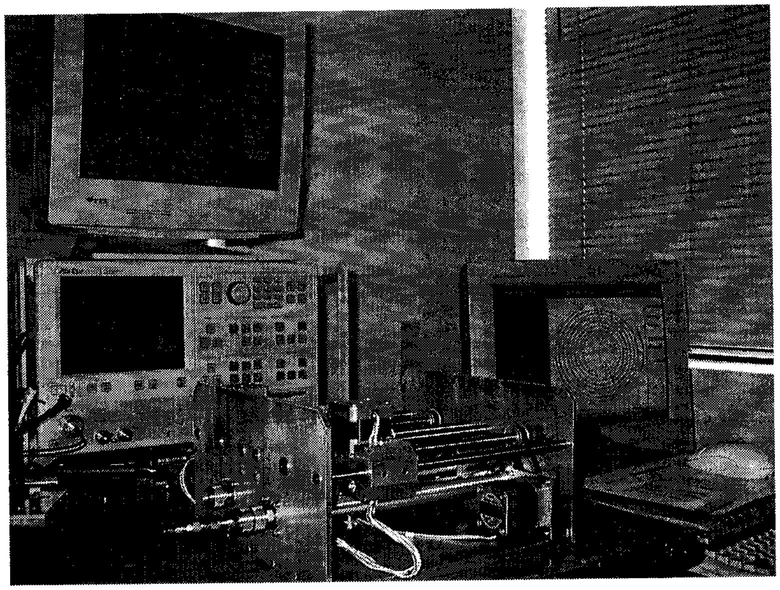

Figure 8.23 DMT Calibration Setup

8.6.2 CALIBRATION RESULT

The calibration points of the DMT are shown on the Smith Chart.

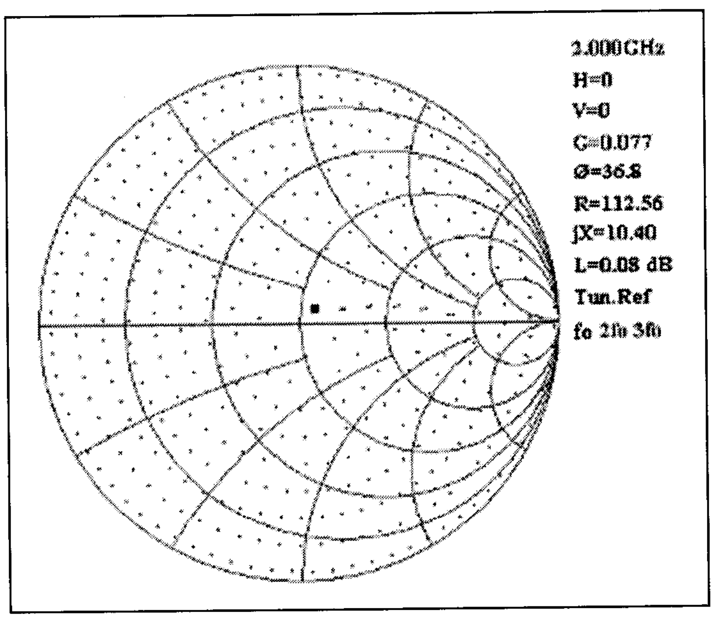

Figure 8.24 DMT Calibration Points

8.7 COMMON MODE INTERFERENCE ANALYSIS

As differential device is characterized in only differential mode in the Differential Load Pull System, it is very important to keep common mode signals small enough to be neglected.

In general common mode signals will be generated due to imbalance of the baluns. In Differential Load Pull System, since the baluns are connected with differential tuner and differential test fixtures, all the connected networks should be balanced as much as possible.

The imbalance of DMT tuner has been studied in previous chapter, we will analyze the imbalance of baluns, differential test fixtures and whole setup in this section.

8.7.1 INPUT BALUN

CMRR represents common mode rejection ratio, and is important parameter in this project. Since the performance of output balun is same as the input balun, we analyze the CMRR of input balun only.

The common mode forward transmission and differential mode forward transmission are shown in the figure 8.25. The difference is the CMRR of transmission.

It shows 30 dB rejections to common mode signals. It implies that common mode signals could be neglected.

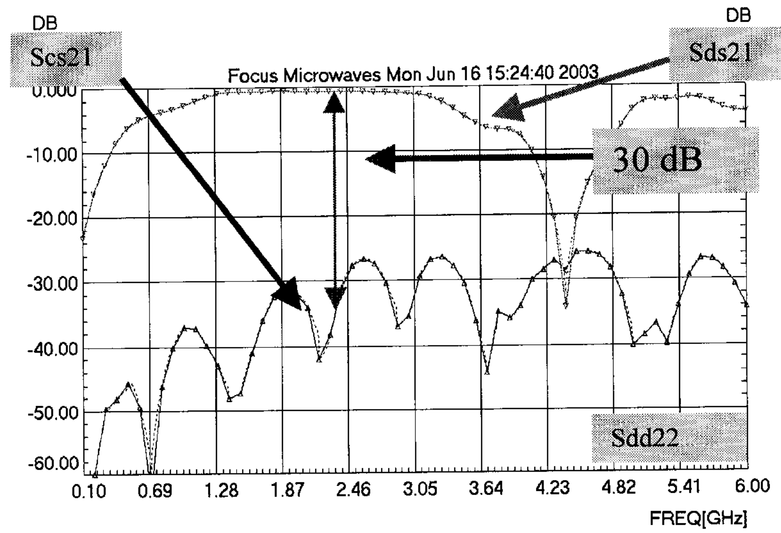

Figure 8.25 CMRR of Input Balun

8.7.2 INPUT TEST FIXTURE

Test fixture contains two 50-Ohm transmission lines, which are not coupled at all. Both common and differential signals pass through test fixture. The common and differential mode S-parameters are shown in figure 8.26.

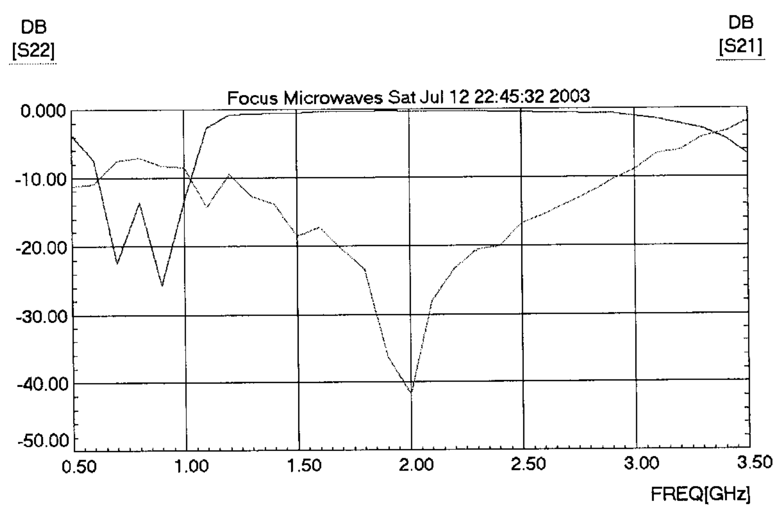

Figure 8.26 Mixed mode S-parameters of Input Test Fixture

8.7.3 IMBALANCE OF SETUP

In the previous sections and chapters, imbalance of DMT, balun and test fixture is discussed. Based on the calibration data of the setup, the investigation of the whole setup is evaluated. However only the input section of the setup is described here since the same rule can be applied to output section too.

The input section diagram is reviewed and shown in figure 8.27.

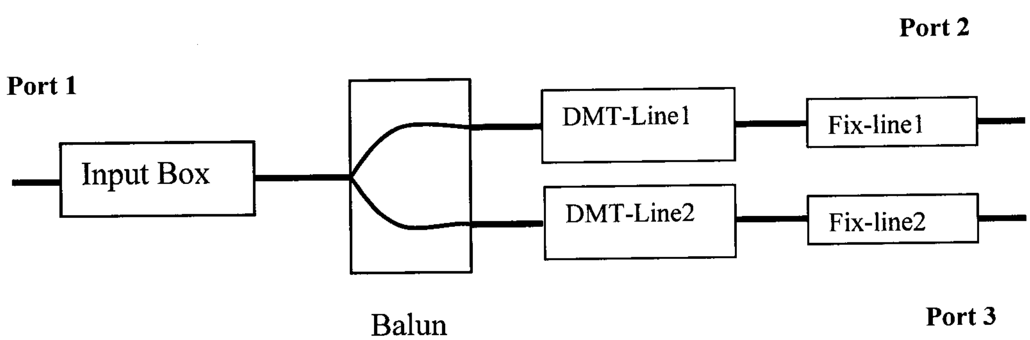

Figure 8.27 Input Section of DLPS

The total 3-ports single-ended S-parameters at operating frequency 2 GHz are calculated, and the results are as follows.

$$\begin{bmatrix} 0.063\angle 150.11 & 0.050\angle 119.62 & 0.050\angle 65.32 \\ 0.536\angle -77.7 & 0.411\angle 48.09 & 0.411\angle 43.57 \\ 0.541\angle 97.31 & 0.411\angle 43.50 & 0.440\angle 38.21 \end{bmatrix}$$

Differential Mode S-parameters are calculated from single-ended S –parameters,

$$\begin{bmatrix} 0.063\angle 150.1 & 0.071\angle 140 \\ 0.761\angle 80.25 & 0.013\angle 25.76 \end{bmatrix}$$

Common Mode S-parameters are as follows,

$$\begin{bmatrix} 0.063\angle 150.1 & 0.003\angle -145.9 \\ 0.033\angle 16.34 & 0.835\angle 43.25 \end{bmatrix}$$

Differential Mode to Common Mode conversion S-parameter Scd is as follows,

$$0.039\angle 155.12$$

CMRR can be calculated then, Sds/Scs, is 27.26 dB. It is enough to guarantee transmitted common mode signals are small enough to interference differentia mode measurement.

Differential mode to common mode conversion is -28.2 dB. As known the mode conversion formula is as follows,

$$S_{cd} = \frac{1}{2}(S_{22} - S_{33})$$

In order to minimize mode conversion, reflection factors at port 2 and port 3 are tuned as close as possible in software so that the mode conversion Scd is very small so that this term can be neglected during the measurement. In this case, the mode conversion is –28.2 dB, small enough to be neglected.

8.8 CONCLUSION

System calibration is very important since it will affect the measurement accuracy. All the components are characterized as single ended devices. In other words standard S-parameters are collected, and then are later transformed to mixed mode S-parameters during the measurement.

Imbalance of baluns may cause common mode signals pass to interfere the measurement. It is very important to select good baluns at operating frequency, align two slab lines of DMT very well and keep test fixture same electrical length and not coupled.

CHAPTER 9

MEASUREMENT AND DATA ANALYSIS

Once the system is calibrated and verified, device measurement is executed. In this chapter, some experiments are done and data is analyzed with very promising results.

9.1 SOFTWARE DEVELOPMENT

The software developed is based on Focus Microwaves WINCCMT [11], [12], which runs standard load pull and source pull for both power and noise measurements. It is written in Microsoft C/C++ and involved Windows programming [26], [37]. It has a friendly user interface and fast calculation speed.

9.1.1 SOFTWARE STRUCTURE

The main software structure is shown in figure 9.1. It includes the following routines:

Differential tuner control (Move) routine,
Differential tuner calibration routine,
Differential test fixture calibration routine,
Balun transition board calibration routine,
Standard two passive components calibration routine,
Mixed mode S-parameters computing routine,
Mixed mode S-parameter cascade routine,
Differential tuner calibration file loading routine,

Network Analysis routine,

Differential tuner tuning routine,

Differential reflection coefficient tuning routine,

Differential loss computing routine,

Differential reference plane de-embedding routine,

RF measurement routine,

Instrument control routine,

Differential load pull and source pull routine,

Data acquiring routine,

Data display and processing routine, etc

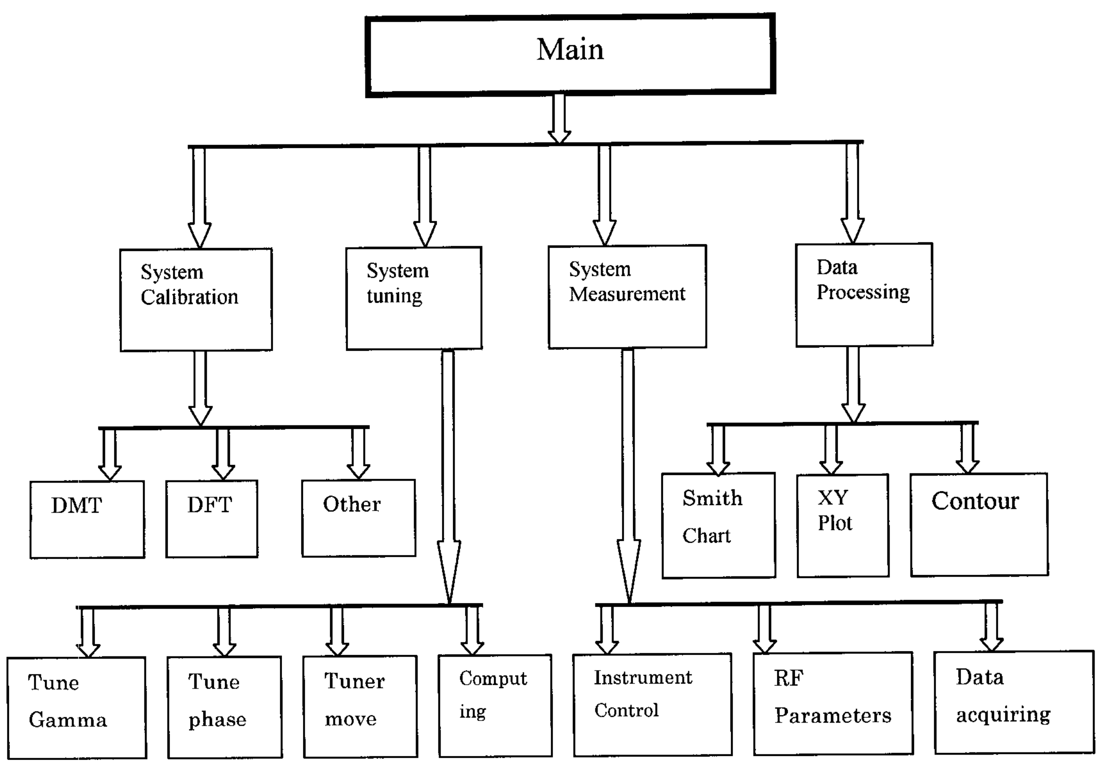

Figure 9.1 Software Structure

9.1.2 USER INTERFACE

The two child windows represent the input and output networks looking away from the DUT reference plane. The reference plane can be shifted manually to that of DUT, Tuner or Fixture to analyze and verify the calibration accuracy.

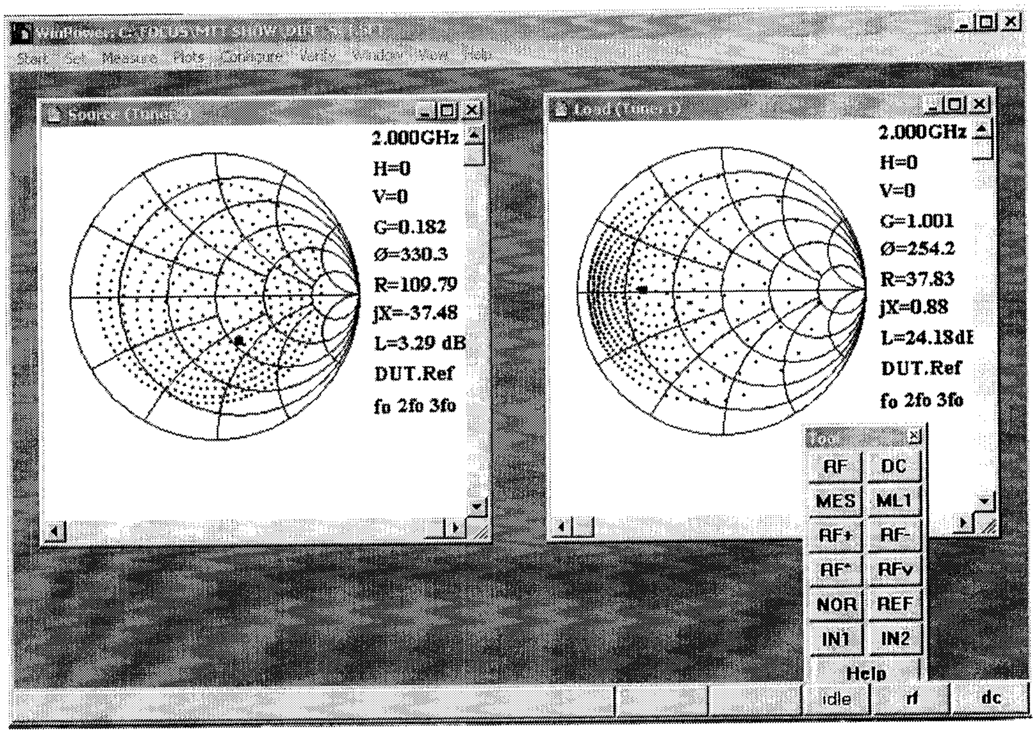

Figure 9.2 Software Operation

On the output Smith Chart, the calibration points shifted because the transformer is used at the differential test fixture in order to match the lower load impedance. All the system information is displayed on the Smith Chart.

a) Frequency: Operating frequency is carried out at 2.0 GHz.

b) Tuner position: H represents the horizontal probe position, and V represents vertical tuner position.

c) Reflection coefficient: It is in magnitude and phase format.

d) Impedance: The impedance at the current tuner position is displayed, it corresponds to the reflection coefficient.

e) Loss of the input or output section, is used to de-embedded raw measurement data (reading from instruments) to the DUT reference plane.

9.2 LOAD SETUP

First of all, all the calibration files of components must be loaded into software. The diagram, shown in figure 9.1, explains all sections in the DLPS.

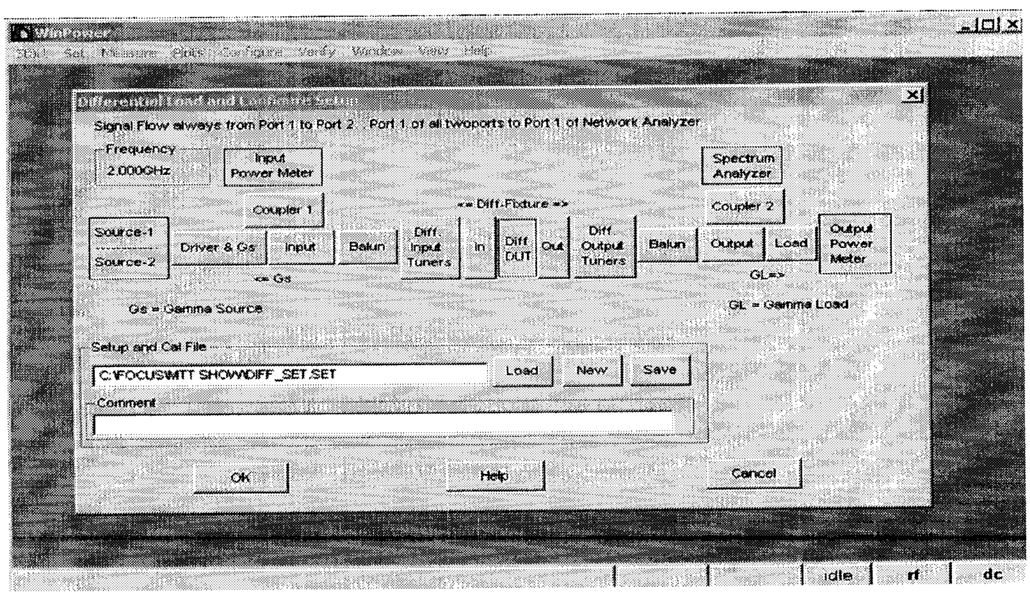

Figure 9.3 Load Setup

With all the calibration files loaded into the setup, the software calculates the measurement data to DUT plane. The user interface is shown in figure 9.3 [9].

The S-parameters of the input block including the coupler bias tee, the isolator is measured as two port passive networks. The S-parameters of those components are cascaded so that the available loss of the input block can be calculated.

For input and output baluns, they are considered a special case. The losses of the balun can be obtained by calculating mixed S-parameters. But once the mixed S-parameters are acquired, they can be used to calculate the differential gain of the network or device directly. The same rule can be applied to the tuner and test fixture.

Finally all the S-parameters of input including tuner and test fixture are cascaded. One thing that should be mentioned here is that the differential mode S-parameters of tuner and test fixture input are cascaded first, and then the differential mode S-parameters of balun is taken for the calculations.

The reflection coefficient seen by the DUT is calculated. The input power at the DUT reference plane is calculated from the measurement power, which is sampled by input power meter through input coupling.

For the output, it is the same as input calculation. The only difference is that the power gain is taken into account since we measure the power delivered to the load.

The reflection coefficient seen by output of the DUT is calculated. The output power at the DUT reference plane is calculated from the measurement power, which is sampled by an output power meter.

Unfortunately, reviewing the setup, there is a small problem with the driver amplifier, which can provide 28 dBm output power. It can be driven a bit harder, but the output power is saturated at 30 dBm. It is not enough to drive DUT (FLL400IP-2) to saturation. But it doesn't affect the load pull measurement much since the major parameter we are looking for is the optimum impedance rather than output power.

9.3 DEVICE SELECTION

Fujitsu Semiconductor provides test devices, with model of FLL400IP-2 and FLL300IP-2. FLL300IP-2 is an obsolete part; it is used to run the setup, while the FLL400IP-2 is the real Device Under Test. All the data shown in this project is for the FLL400IP-2.

9.4 MEASURMENT ARRANGEMENT

The measurement procedure is the following,

1) Configure all the instruments and set proper limits for the power supply and signal generator.

2) Bias the device.

3) Measure the IV characteristics in order to bias the transistor properly.

4) Sweep the input power to determine the maximum input power level.

5) Match the input manually.

6) Load pull measurement

9.5 RF PARAMETERS

The measured parameters are Gain, Pin, Pout, Ids, Igs, Vds, Vgs, P.A.E. The definitions of these parameters are the following:

Gain
Transducer Gain = Pout.delivered/Pin.available (=injected)

Ids
Output Current (Drain Current or Collector Current)

Igs
Input Current (Gate Current or Base Current)

P.A.Eff
Power added Efficiency = (Pout-Pin)/Pdc

Pin
Power Injected at the DUT input port

Pout
Power Delivered at the Load of the setup

Vds
Output DC Bias Voltage (Drain or Collector Voltage)

Vgs
Input (Control) voltage (Gate or Base)

9.6 SELECT BIAS CONDITION (IV CURVES)

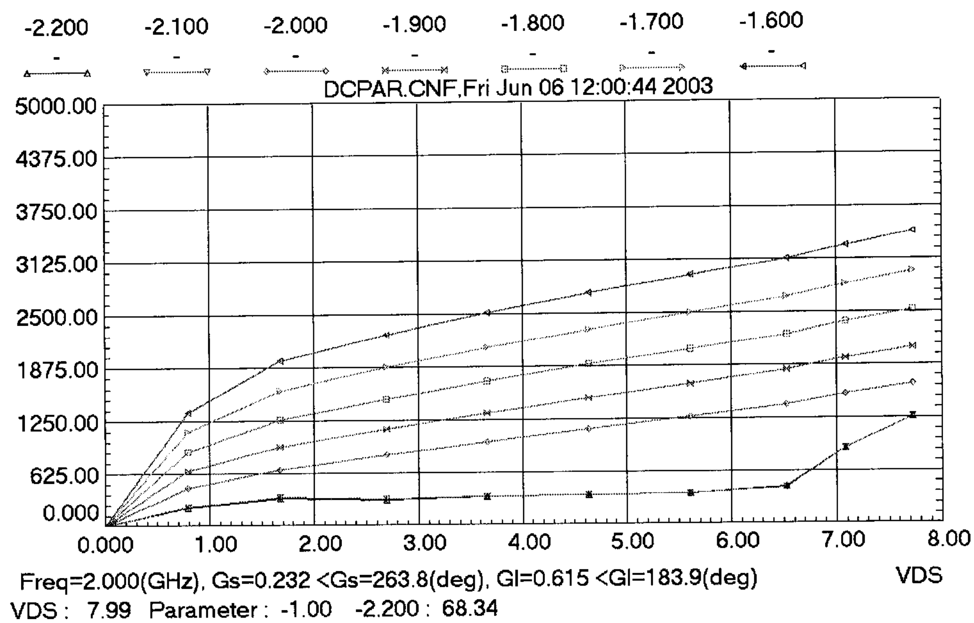

Figure 9.4 IV Curves

9.7 POWER SWEEP

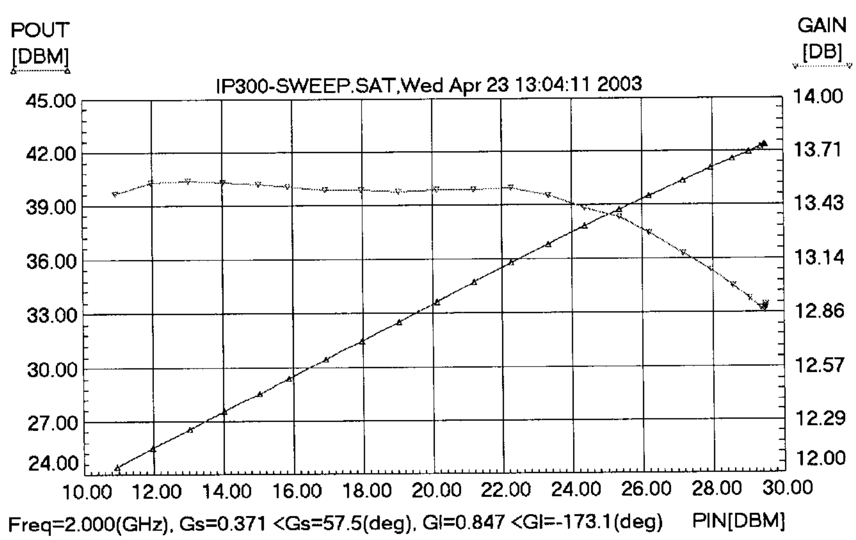

Figure 9.5 Output Power and Gain vs. Input Power

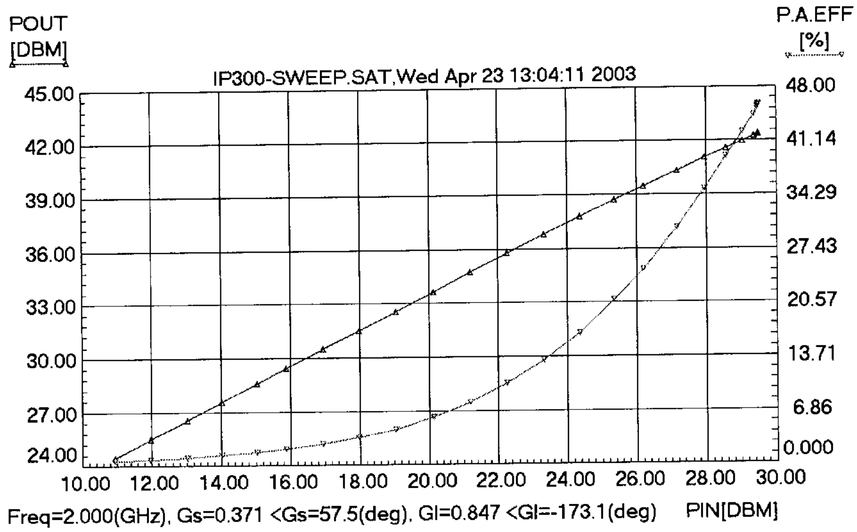

Figure 9.6 Output Power and Power Added Efficiency vs. Input Power

9.8 LOAD PULLMEASUREMENT

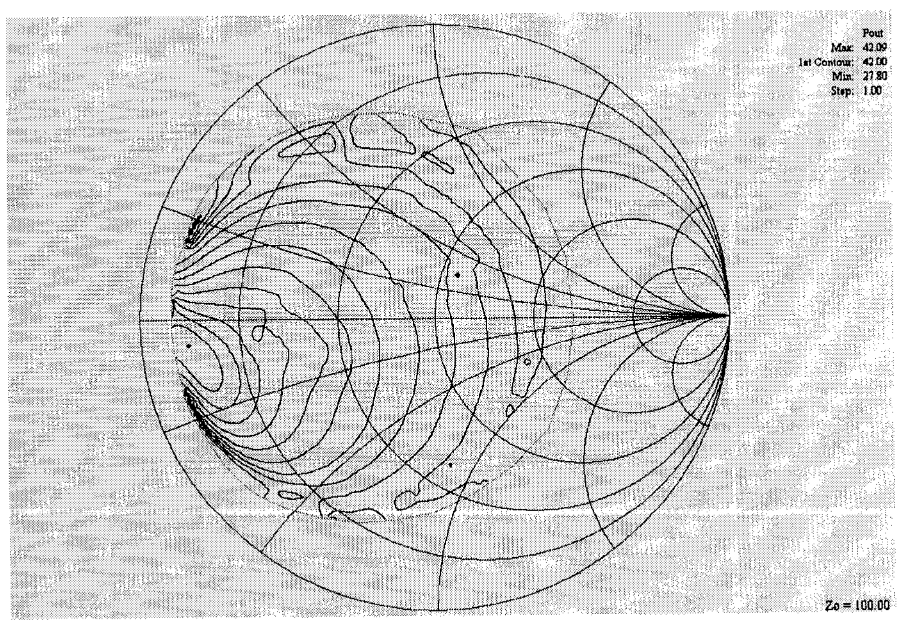

Figure 9.7 Load Pull Contour

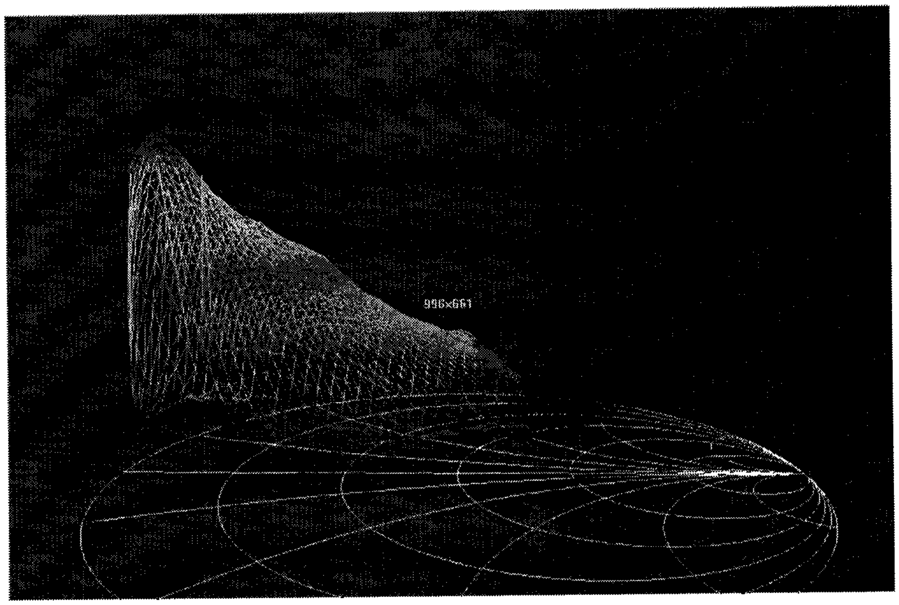

Figure 9.8 Load Pull Contour with 3-Dimension View

The optimum impedance is:

9.7-j*6.2 Ohm (0.83 < -172 degree)

9.9 DATA ANALYSIS

Fujitsu has performed some measurements by tuning a matching network manually.

Table 9.1 FLL400IP-2 Optimum Load/Source Impedance

Frequency (GHz)	ZT.F.In (Ohm)	ZT.F.Out (Ohm)
1.93	35.0 + j109	9.0 - j17.2
1.96	32.5 +j100	8.5 - j17.2
1.99	31.5 + j92	8.0 - j17.2

Test Conditions are listed below:

Bias : VDS = 12.0V, IDSQ = 2.0A
Frequency : 1.93 GHz – 1.99 GHz

Test signal is IS-95 CDMA source.

9.10 CONCLUSION

The above results show that they are very close. But the measurement from S-parameters or manual tuning is not accurate since the device is not working in real operating conditions.

CHAPTER 10
CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

This thesis presents a systematic framework for balanced microwave device characterization. The Differential Load Pull System was developed and built in this project. The Differential Load Pull System theory, the Differential Microwave Tuners, the new, innovative system calibration procedure, introduced mixed mode S-parameters, and a new de-embedding method of Differential Test Fixture are the main contributions of this thesis.

The DMT tuner is designed with two independent slab lines to present a differential reflection coefficient to the input and output of the DUT. The two independent slab lines are completely isolated so that the calibration and tuning control becomes easier. S-parameters of each slab line with varied probe positions give enough information for characterization of the tuner. Since two slab lines can be tuned independently, it provides a good margin to optimize the reflection factor of each line by the software. Furthermore, the developed DMT can be used as two single-ended tuners.

TRL technique is extended to calibrate Differential Test Fixtures (DFT). The DFT is designed to have not only good return loss at the center frequency 2 GHz, but also good amplitude and transmission phase balance. Based on the design, two transmission lines on the DTF are uncoupled. This makes it possible to use two-port TRL technique to calibrate four-port DFT.

The microwave balun is the key element in the balanced circuits. The unbalanced characteristic performance and balanced characteristic performance are analyzed. Broadband transformers are designed to match the balun to the DMT tuner. Differential impedance of the system is also defined in this project (as 100 ohms). The unique characterization method of the microwave balun is also presented. It is simple, easy and able to be implemented using existing two port instruments.

Balanced components, including baluns, DMTs, DTF, and unbalanced components, including couplers, isolators, combiners (splitters), attenuators as well as RF cables, are calibrated using Vector Network Analyzer. The three ports network analysis is introduced to calculate mixed mode S-parameters instead of using traditional S-parameters cascading.

The software provides a user-friendly interface. All the data is easy to access since they are shown on the Smith Chart. Microsoft C++ is used for programming so that the performance of the software relatively fast.

Finally push pull devices, provided by Fujitsu, are tested using the developed Differential Load Pull System and results are excellent.

10.2 RECOMMENDATIONS

Based on the results and experience gained from this research work the following recommendations can be made:

1) The reflection factor presented at DUT reference plane is not high enough due to the loss of the Differential Test Fixture. This is a reason to use a transformer on the output of the differential test fixture. However, the transformer is usually narrow band, therefore it must be replaced if the test frequency is changed. Pre-matching DMT tuners could improve the reflection factor.

2) Harmonic tuning is needed [3], [32], since the cancellation of even harmonics may not be desired for the design. For example the efficiency could be improved by harmonic tuning. This would give additional information for amplifier circuit design.

3) Microwave baluns play an important role in the system. Unfortunately the balanced two ports of a balun only have 6dB isolation, this may cause the device to become unstable. In fact the 3-db 180-degree hybrid coupler can also be used to split input signal and combine output signals. The transformers designed to match the balun to the DMT is not necessary since a coupler has 50 Ohm at each port. Also, 180-degree couplers have better isolation performance than baluns. However, the commercially available 180-degree coaxial coupler does not give good phase and amplitude balance. The surface mount coupler requires additional 50-ohm load for one isolated port that will be difficult to implement on planar and cost more.

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APPENDIX A

Load Pull Measurement Data

!---
! File = C:\FOCUS\DMT\APRIL-24\IP400\BIAS-GATE17-DRAIN12\IP300-TRANSFORMER-FULL.LPD
! Date = Thu Apr 24 14:39:30 2003
!---
! Comment =
! Frequency = 2.0000 GHz
! Char.Impedances = Source: 100.00 Ohm, Load: 100.00 Ohm
! Source Impedance = 112.65 +j 33.36 Ohm
! Input Power = 29.51 dBm
! GAMMA_SR = Gs1fo=0.371<57.5(deg)
! IMPED_SR = Zs1fo=58.34+j42.33
! Setup: DMT3.SET, DUT REF.
! PreMatch:
! Gamma/Phi
!---

Point	Gamma	Phase	Pin[dBm]	Pout[dBm]	Gain[dB]	Igs[mA]	Vgs[V]	Ids[mA]	Vds[V]	P.A.Eff[%]
001	0.4426	-170.05	29.51	37.53	8.02	-2.1831889	-2.9096150	3463.00	12.0050001	11.47
002	0.3996	-163.48	29.51	37.35	7.84	-2.1588409	-2.9095521	3496.40	12.0050001	10.81
003	0.5597	-159.60	29.51	38.10	8.59	-2.1913049	-2.9095869	3545.90	12.0050001	13.06
004	0.6607	-166.51	29.51	39.57	10.06	-2.1872470	-2.9096270	3461.50	12.0050001	19.63
005	0.6954	-174.39	29.51	39.57	10.05	-2.1750729	-2.9095681	3319.00	12.0050001	20.46
006	0.6860	177.85	29.51	38.27	8.75	-2.1142030	-2.9095840	3282.70	12.0050001	14.75
007	0.6371	170.05	29.51	36.94	7.43	-2.1669569	-2.9095719	3311.80	12.0050001	10.20
008	0.5350	163.75	29.51	36.17	6.66	-2.1791310	-2.9095600	3368.50	12.0050001	8.02
009	0.3874	169.53	29.51	35.99	6.48	-2.1020291	-2.9096191	3419.40	12.0050001	7.49
010	0.3983	-163.71	29.51	37.33	7.82	-2.2156529	-2.9095280	3487.70	12.0050001	10.79
011	0.3721	-154.33	29.51	36.68	7.17	-2.1344931	-2.9094760	3541.50	12.0050001	8.85
012	0.3607	-155.26	29.51	36.68	7.18	-2.1669569	-2.9094090	3543.00	12.0050001	8.85
013	0.2882	-175.07	29.51	35.79	6.28	-2.1507251	-2.9094410	3454.30	12.0050001	6.99
014	0.3375	162.37	29.51	35.38	5.87	-2.1872470	-2.9094200	3449.90	12.0050001	6.18
015	0.4481	155.99	29.51	35.44	5.93	-2.2034791	-2.9094560	3426.60	12.0050001	6.33
016	0.5465	157.93	29.51	35.59	6.07	-2.2318850	-2.9095199	3394.60	12.0050001	6.69
017	0.6152	162.30	29.51	35.91	6.40	-2.2521741	-2.9095120	3362.60	12.0050001	7.45
018	0.6647	166.94	29.51	36.41	6.90	-2.2481160	-2.9094880	3332.10	12.0050001	8.70
019	0.6980	171.51	29.51	37.11	7.59	-2.2318850	-2.9094999	3304.50	12.0050001	10.70
020	0.7194	175.93	29.51	38.00	8.48	-2.2237680	-2.9094999	3279.80	12.0050001	13.74
021	0.7320	-179.82	29.51	38.99	9.48	-2.1466670	-2.9094880	3263.80	12.0050001	17.96
022	0.7358	-175.65	29.51	39.93	10.42	-2.1872470	-2.9095161	3266.70	12.0050001	22.83
023	0.7307	-171.42	29.51	40.51	10.99	-2.2359421	-2.9095120	3307.40	12.0050001	26.05
024	0.7145	-166.89	29.51	40.47	10.96	-2.1182611	-2.9095120	3399.00	12.0050001	25.10
025	0.6814	-162.25	29.51	39.80	10.29	-2.1791310	-2.9095480	3503.70	12.0050001	20.57
026	0.6282	-157.25	29.51	38.75	9.24	-2.1628988	-2.9094639	3564.80	12.0050001	15.41
027	0.5427	-152.87	29.51	37.58	8.07	-2.1628988	-2.9095359	3570.60	12.0050001	11.28
028	0.4497	-142.74	29.51	36.29	6.79	-2.0695660	-2.9095080	3582.20	12.0050001	7.83
029	0.5428	-146.23	29.51	37.13	7.63	-2.0776820	-2.9095080	3631.70	12.0050001	9.80
030	0.6199	-150.54	29.51	38.11	8.60	-2.0898550	-2.9095240	3672.40	12.0050001	12.65
031	0.6728	-155.03	29.51	39.09	9.59	-2.2115951	-2.9095120	3685.50	12.0050001	16.32
032	0.7103	-159.16	29.51	40.03	10.52	-2.1304350	-2.9094679	3653.50	12.0050001	20.90
033	0.7361	-163.08	29.51	40.77	11.27	-2.1710148	-2.9095600	3561.90	12.0050001	25.86
034	0.7552	-166.46	29.51	41.28	11.78	-2.1507251	-2.9095681	3438.30	12.0050001	30.39

035	0.7658	-169.71	29.51	41.41	11.90	-2.2521741	-2.9094801	3326.30	12.0050001	32.39
036	0.7714	-172.90	29.51	41.12	11.60	-2.2805800	-2.9095280	3252.10	12.0050001	30.83
037	0.7725	-175.87	29.51	40.46	10.94	-2.2278271	-2.9094479	3217.20	12.0050001	26.44
038	0.7705	-178.82	29.51	39.57	10.05	-2.1588409	-2.9095161	3208.50	12.0050001	21.18
039	0.7637	178.25	29.52	38.64	9.12	-2.1953630	-2.9096110	3217.20	12.0050001	16.61
040	0.7547	175.22	29.51	37.77	8.26	-2.1750729	-2.9094920	3231.80	12.0050001	13.12
041	0.7415	172.08	29.51	37.01	7.50	-2.2359421	-2.9095440	3250.70	12.0050001	10.58
042	0.7236	168.77	29.51	36.38	6.87	-2.2278271	-2.9095120	3272.50	12.0050001	8.80
043	0.7004	165.22	29.51	35.86	6.35	-2.2197111	-2.9095199	3295.80	12.0050001	7.49
044	0.6698	161.49	29.51	35.46	5.94	-2.1385510	-2.9095521	3320.50	12.0050001	6.57
045	0.6291	157.54	29.51	35.15	5.64	-2.2075360	-2.9095750	3345.20	12.0050001	5.92
046	0.5756	153.39	29.51	34.95	5.44	-2.1385510	-2.9095640	3372.80	12.0050001	5.51
047	0.5040	149.59	29.51	34.83	5.32	-2.1710148	-2.9096069	3401.90	12.0050001	5.26
048	0.4105	147.63	29.51	34.82	5.31	-2.1304350	-2.9095399	3431.00	12.0050001	5.19
049	0.3071	150.49	29.51	34.83	5.32	-2.1385510	-2.9096310	3460.10	12.0050001	5.17
050	0.2211	169.30	29.51	34.91	5.40	-2.1588409	-2.9095120	3487.70	12.0050001	5.26
051	0.2376	-158.15	29.51	35.30	5.79	-2.1466670	-2.9095869	3528.40	12.0050001	5.89
052	0.3341	-144.29	29.51	35.76	6.25	-2.1426091	-2.9095910	3570.60	12.0050001	6.70
053	0.3907	-140.92	29.51	35.90	6.40	-2.1020291	-2.9096229	3586.60	12.0050001	6.97
054	0.3843	-132.45	29.51	35.41	5.91	-2.1669569	-2.9096630	3608.40	12.0050001	5.97
055	0.3784	-132.14	29.51	35.38	5.88	-2.1466670	-2.9096069	3612.80	12.0050001	5.90
056	0.2615	-132.65	29.51	34.89	5.38	-2.1182611	-2.9096870	3582.20	12.0050001	5.09
057	0.1705	-143.11	29.51	34.59	5.08	-2.1344931	-2.9096191	3550.20	12.0050001	4.66
058	0.1509	168.41	29.51	34.40	4.89	-2.1466670	-2.9096670	3527.00	12.0050001	4.40
059	0.2318	141.69	29.51	34.24	4.73	-2.1831889	-2.9096310	3503.70	12.0050001	4.19
060	0.3468	136.31	29.51	34.13	4.62	-2.2521741	-2.9096949	3480.40	12.0050001	4.05
061	0.4488	138.84	29.51	34.08	4.57	-2.2034791	-2.9096589	3458.60	12.0050001	4.02
062	0.5266	143.09	29.51	34.12	4.61	-2.1142030	-2.9096670	3438.30	12.0050001	4.09
063	0.5891	147.56	29.51	34.19	4.67	-2.1953630	-2.9097300	3419.40	12.0050001	4.21
064	0.6368	151.78	29.51	34.31	4.80	-2.1507251	-2.9096911	3397.50	12.0050001	4.43
065	0.6740	155.59	29.51	34.49	4.98	-2.2197111	-2.9096711	3377.20	12.0050001	4.73
066	0.7040	159.17	29.51	34.74	5.23	-2.1994209	-2.9096310	3356.80	12.0050001	5.17
067	0.7274	162.37	29.51	35.04	5.53	-2.1913049	-2.9096630	3337.90	12.0050001	5.74
068	0.7461	165.39	29.51	35.44	5.92	-2.2359421	-2.9096150	3319.00	12.0050001	6.53
069	0.7615	168.21	29.51	35.91	6.39	-2.2237680	-2.9095719	3300.10	12.0050001	7.58
070	0.7740	170.89	29.52	36.48	6.96	-2.1710148	-2.9095991	3282.70	12.0050001	9.01
071	0.7839	173.37	29.52	37.14	7.62	-2.2684062	-2.9095161	3265.20	12.0050001	10.91
072	0.7920	175.79	29.52	37.91	8.39	-2.2724640	-2.9095321	3247.80	12.0050001	13.56
073	0.7978	178.10	29.52	38.78	9.26	-2.2521741	-2.9094880	3230.30	12.0050001	17.17
074	0.8035	-179.60	29.52	39.74	10.22	-2.3089859	-2.9095399	3217.20	12.0050001	22.07
075	0.8058	-177.37	29.52	40.63	11.12	-2.2521741	-2.9093969	3210.00	12.0050001	27.69
076	0.8071	-175.11	29.52	41.38	11.86	-2.2318850	-2.9093771	3211.40	12.0050001	33.32
077	0.8058	-172.74	29.51	41.90	12.38	-2.2440581	-2.9094250	3233.20	12.0050001	37.55
078	0.8035	-170.28	29.51	42.06	12.55	-2.2318850	-2.9094090	3278.30	12.0050001	38.54
079	0.7976	-167.79	29.51	41.95	12.44	-2.2156529	-2.9094801	3353.90	12.0050001	36.65
080	0.7888	-165.11	29.51	41.63	12.13	-2.1913049	-2.9094639	3457.20	12.0050001	32.95
081	0.7766	-162.22	29.51	41.16	11.65	-2.1628988	-2.9093850	3573.50	12.0050001	28.35
082	0.7568	-159.07	29.50	40.49	10.99	-2.1872470	-2.9095120	3676.70	12.0050001	23.36
083	0.7343	-155.59	29.50	39.73	10.23	-2.2075360	-2.9094200	3739.30	12.0050001	18.95
084	0.7029	-151.71	29.50	38.90	9.40	-2.2075360	-2.9094760	3755.30	12.0050001	15.23
085	0.6621	-147.36	29.50	38.02	8.52	-2.1466670	-2.9094720	3740.70	12.0050001	12.14
086	0.6038	-142.71	29.50	37.16	7.66	-2.1710148	-2.9094601	3708.70	12.0050001	9.69
087	0.5307	-137.64	29.50	36.37	6.87	-2.1913049	-2.9095161	3673.80	12.0050001	7.81
088	0.4966	-125.81	29.50	35.29	5.79	-2.1507251	-2.9094319	3669.50	12.0050001	5.65
089	0.5754	-132.13	29.50	35.92	6.42	-2.1913049	-2.9094801	3721.80	12.0050001	6.76
090	0.6361	-137.91	29.50	36.62	7.12	-2.1385510	-2.9094369	3775.60	12.0050001	8.17
091	0.6832	-142.94	29.50	37.37	7.87	-2.1060870	-2.9095359	3832.30	12.0050001	9.93
092	0.7228	-147.28	29.50	38.15	8.65	-2.1791310	-2.9094319	3893.40	12.0050001	12.06

093	0.7511	-151.18	29.50	38.90	9.40	-2.2602901	-2.9094169	3935.60	12.0050001	14.55
094	0.7736	-154.65	29.50	39.62	10.12	-2.2197111	-2.9094679	3944.30	12.0050001	17.46
095	0.7908	-157.73	29.50	40.23	10.73	-2.1588409	-2.9094560	3900.70	12.0050001	20.61
096	0.8059	-160.56	29.50	40.71	11.21	-2.1547830	-2.9094920	3807.60	12.0050001	23.82
097	0.8165	-163.14	29.51	41.09	11.58	-2.2278271	-2.9094880	3697.10	12.0050001	26.92
098	0.8244	-165.46	29.51	41.41	11.90	-2.1994209	-2.9095640	3601.10	12.0050001	29.94
099	0.8300	-167.68	29.51	41.69	12.18	-2.1831889	-2.9095869	3509.50	12.0050001	32.94
100	0.8343	-169.75	29.51	41.91	12.40	-2.1669569	-2.9095521	3415.00	12.0050001	35.71
101	0.8367	-171.78	29.51	42.07	12.56	-2.2521741	-2.9094839	3317.60	12.0050001	38.20
102	0.8381	-173.68	29.52	42.09	12.57	-2.2481160	-2.9095640	3249.20	12.0050001	39.15
103	0.8385	-175.55	29.52	41.84	12.32	-2.1953630	-2.9095800	3210.00	12.0050001	37.32
104	0.8374	-177.37	29.52	41.31	11.79	-2.2197111	-2.9095240	3191.10	12.0050001	32.97
105	0.8357	-179.21	29.52	40.52	11.00	-2.2765222	-2.9095750	3188.20	12.0050001	27.09
106	0.8314	178.90	29.52	39.51	9.99	-2.2156529	-2.9095681	3195.40	12.0050001	20.96
107	0.8272	177.04	29.52	38.54	9.02	-2.2724640	-2.9094880	3207.10	12.0050001	16.23
108	0.8228	175.16	29.52	37.64	8.12	-2.2034791	-2.9094880	3220.10	12.0050001	12.69
109	0.8172	173.20	29.52	36.82	7.30	-2.2359421	-2.9094410	3234.70	12.0050001	10.08
110	0.8100	171.17	29.52	36.14	6.62	-2.2481160	-2.9095359	3249.20	12.0050001	8.24
111	0.8021	169.07	29.52	35.55	6.03	-2.2156529	-2.9095840	3263.80	12.0050001	6.87
112	0.7921	166.80	29.52	35.06	5.54	-2.1913049	-2.9095399	3278.30	12.0050001	5.87
113	0.7810	164.43	29.52	34.64	5.13	-2.1710148	-2.9094999	3294.30	12.0050001	5.10
114	0.7679	161.90	29.51	34.29	4.78	-2.1344931	-2.9096069	3310.30	12.0050001	4.51
115	0.7520	159.12	29.51	34.00	4.48	-2.1791310	-2.9095750	3327.70	12.0050001	4.05
116	0.7324	156.19	29.51	33.78	4.27	-2.2805800	-2.9095280	3343.70	12.0050001	3.72
117	0.7093	152.82	29.51	33.58	4.07	-2.2318850	-2.9095910	3361.20	12.0050001	3.44
118	0.6794	149.21	29.51	33.46	3.95	-2.2034791	-2.9096031	3381.60	12.0050001	3.27
119	0.6429	145.13	29.51	33.39	3.87	-2.2156529	-2.9095640	3400.50	12.0050001	3.15
120	0.5969	140.57	29.51	33.34	3.83	-2.1831889	-2.9094920	3420.80	12.0050001	3.08
121	0.5397	135.46	29.51	33.32	3.81	-2.2075360	-2.9095719	3439.70	12.0050001	3.04
122	0.4689	129.78	29.51	33.32	3.81	-2.1344931	-2.9095521	3460.10	12.0050001	3.02
123	0.4214	119.33	29.51	33.15	3.64	-2.1628988	-2.9095240	3479.00	12.0050001	2.80
124	0.3377	106.67	29.51	33.11	3.60	-2.2115951	-2.9095280	3503.70	12.0050001	2.74
125	0.2265	86.01	29.51	33.13	3.62	-2.1344931	-2.9095681	3529.90	12.0050001	2.74
126	0.0327	166.29	29.51	33.72	4.21	-2.1020291	-2.9095559	3559.00	12.0050001	3.42
127	0.1317	-110.93	29.51	33.98	4.48	-2.2237680	-2.9095240	3586.60	12.0050001	3.74
128	0.2657	-111.73	29.51	34.23	4.72	-2.1385510	-2.9095600	3605.50	12.0050001	4.06
129	0.3837	-118.65	29.51	34.68	5.17	-2.1953630	-2.9095910	3646.20	12.0050001	4.67
130	0.4463	-122.29	29.51	34.99	5.48	-2.1547830	-2.9095161	3672.40	12.0050001	5.12
131	0.5162	-117.28	29.50	34.46	4.96	-2.0857980	-2.9095480	3705.80	12.0050001	4.27
132	0.4837	-113.88	29.51	34.26	4.75	-2.1182611	-2.9094880	3698.50	12.0050001	3.99
133	0.3884	-103.87	29.51	33.80	4.29	-2.1710148	-2.9095199	3669.50	12.0050001	3.42
134	0.2810	-90.30	29.51	33.40	3.89	-2.1466670	-2.9095161	3641.80	12.0050001	2.96
135	0.1669	-66.88	29.51	33.05	3.54	-2.1994209	-2.9095080	3602.60	12.0050001	2.60
136	0.0738	-5.57	29.51	32.90	3.39	-2.1913049	-2.9095039	3585.10	12.0050001	2.45
137	0.2504	54.18	29.51	32.23	2.72	-2.1628988	-2.9095321	3567.70	12.0050001	1.82
138	0.3358	82.84	29.51	32.16	2.65	-2.1669569	-2.9095840	3548.80	12.0050001	1.76
139	0.4172	100.50	29.51	32.14	2.63	-2.1913049	-2.9095280	3531.30	12.0050001	1.76
!140	0.4495	115.57	29.51	32.39	2.88	-2.2034791	-2.9095120	3513.90	12.0050001	1.99
!141	0.5240	123.41	29.51	32.35	2.83	-2.1994209	-2.9095600	3496.40	12.0050001	1.96
142	0.5846	129.85	29.51	32.32	2.80	-2.1791310	-2.9094920	3480.40	12.0050001	1.94
143	0.6330	135.37	29.51	32.32	2.80	-2.1426091	-2.9095359	3464.40	12.0050001	1.95
144	0.6723	140.17	29.51	32.34	2.82	-2.1628988	-2.9095321	3449.90	12.0050001	1.98
145	0.7043	144.42	29.51	32.39	2.87	-2.2034791	-2.9094760	3433.90	12.0050001	2.03
146	0.7308	148.14	29.51	32.46	2.94	-2.2765222	-2.9095869	3416.40	12.0050001	2.11
147	0.7527	151.41	29.51	32.56	3.04	-2.1831889	-2.9094999	3400.50	12.0050001	2.22
148	0.7698	154.44	29.51	32.72	3.20	-2.2197111	-2.9095800	3384.50	12.0050001	2.40
149	0.7845	157.16	29.51	32.91	3.40	-2.1913049	-2.9096069	3371.40	12.0050001	2.62
150	0.7968	159.65	29.52	33.16	3.65	-2.1872470	-2.9095559	3356.80	12.0050001	2.92

151	0.8077	161.98	29.52	33.44	3.93	-2.1913049	-2.9095480	3343.70	12.0050001	3.28
152	0.8164	164.13	29.52	33.78	4.26	-2.2197111	-2.9096069	3330.70	12.0050001	3.73
153	0.8247	166.14	29.52	34.15	4.63	-2.1304350	-2.9095840	3316.10	12.0050001	4.28
154	0.8327	168.04	29.52	34.60	5.09	-2.2115951	-2.9095440	3304.50	12.0050001	5.02
155	0.8382	169.87	29.52	35.17	5.65	-2.2359421	-2.9096589	3291.40	12.0050001	6.06
156	0.8438	171.62	29.52	35.82	6.31	-2.2115951	-2.9096110	3278.30	12.0050001	7.44
157	0.8486	173.27	29.52	36.61	7.08	-2.2643480	-2.9095750	3265.20	12.0050001	9.39
158	0.8523	174.89	29.52	37.51	7.99	-2.2562320	-2.9095719	3252.10	12.0050001	12.15
159	0.8557	176.46	29.52	38.52	8.99	-2.2521741	-2.9095480	3240.50	12.0050001	15.96
160	0.8589	178.00	29.52	39.54	10.01	-2.2359421	-2.9095480	3228.90	12.0050001	20.87
161	0.8610	179.54	29.52	40.45	10.93	-2.3008699	-2.9095559	3221.60	12.0050001	26.38
162	0.8647	-178.85	29.52	41.12	11.60	-2.2521741	-2.9095719	3224.50	12.0050001	31.09
163	0.8661	-177.35	29.52	41.35	11.82	-2.3049278	-2.9095480	3240.50	12.0050001	32.73
164	0.8667	-175.81	29.52	41.38	11.86	-2.2359421	-2.9096069	3275.40	12.0050001	32.69
165	0.8666	-174.24	29.52	41.38	11.86	-2.2684062	-2.9096830	3342.30	12.0050001	31.98
166	0.8659	-172.65	29.51	41.34	11.82	-2.2886958	-2.9096110	3442.60	12.0050001	30.76
167	0.8647	-171.01	29.51	41.27	11.75	-2.3130438	-2.9095521	3564.80	12.0050001	29.19
168	0.8624	-169.29	29.51	40.99	11.48	-2.2765222	-2.9096110	3685.50	12.0050001	26.38
169	0.8592	-167.52	29.51	40.62	11.11	-2.2602901	-2.9094520	3774.20	12.0050001	23.48
170	0.8553	-165.63	29.51	40.24	10.73	-2.2481160	-2.9095321	3820.70	12.0050001	21.09
171	0.8501	-163.61	29.51	39.92	10.42	-2.2481160	-2.9095039	3830.90	12.0050001	19.42
172	0.8429	-161.43	29.50	39.73	10.22	-2.2400000	-2.9095559	3849.80	12.0050001	18.38
173	0.8328	-159.14	29.50	39.56	10.05	-2.2359421	-2.9094250	3913.70	12.0050001	17.31
174	0.8228	-156.57	29.50	39.25	9.75	-2.3171020	-2.9094720	3999.50	12.0050001	15.67
175	0.8092	-153.73	29.50	38.81	9.31	-2.2197111	-2.9094760	3999.50	11.8830004	14.12
176	0.7929	-150.63	29.50	38.26	8.76	-2.1426091	-2.9095559	3999.50	11.8879995	12.22
177	0.7726	-147.10	29.50	37.67	8.17	-2.1304350	-2.9094169	3999.50	11.9580002	10.36
178	0.7473	-143.14	29.50	37.05	7.55	-2.1953630	-2.9095440	3971.90	12.0050001	8.77
179	0.7120	-138.60	29.50	36.42	6.92	-2.1791310	-2.9096110	3915.20	12.0050001	7.43
180	0.6719	-133.38	29.50	35.79	6.29	-2.1872470	-2.9095280	3862.90	12.0050001	6.26
181	0.6213	-127.25	29.50	35.19	5.68	-2.1750729	-2.9095039	3814.90	12.0050001	5.26
182	0.6414	-119.16	29.50	33.93	4.43	-2.1953630	-2.9095161	3807.60	12.0050001	3.45
183	0.6922	-126.11	29.50	34.38	4.88	-2.2400000	-2.9095161	3859.90	12.0050001	3.99
184	0.7303	-131.98	29.50	34.88	5.38	-2.2359421	-2.9095161	3919.60	12.0050001	4.64
185	0.7616	-137.05	29.50	35.40	5.90	-2.1710148	-2.9095280	3992.30	12.0050001	5.38
186	0.7857	-141.48	29.50	35.90	6.40	-2.2115951	-2.9095681	3999.50	11.8710003	6.32
187	0.8073	-145.34	29.50	36.35	6.85	-2.1588409	-2.9095120	3999.50	11.7379999	7.29
188	0.8236	-148.72	29.50	36.79	7.29	-2.1507251	-2.9095399	3999.50	11.6099997	8.37
189	0.8368	-151.76	29.50	37.19	7.69	-2.1791310	-2.9096229	3999.50	11.5640001	9.38
190	0.8476	-154.47	29.50	37.45	7.95	-2.1304350	-2.9095399	3999.50	11.6389999	10.04
191	0.8570	-156.96	29.50	37.61	8.11	-2.2359421	-2.9095600	3999.50	11.7550001	10.37
192	0.8636	-159.26	29.50	37.80	8.30	-2.1953630	-2.9095800	3999.50	11.8009996	10.89
193	0.8696	-161.42	29.50	38.02	8.51	-2.2521741	-2.9095280	3999.50	11.7609997	11.57
194	0.8743	-163.33	29.50	38.42	8.91	-2.2521741	-2.9096069	3999.50	11.6330004	13.01
195	0.8806	-165.11	29.50	38.86	9.35	-2.2359421	-2.9095869	3999.50	11.5349998	14.73
196	0.8840	-166.81	29.50	39.48	9.98	-2.3252180	-2.9096229	3999.50	11.6619997	17.11
197	0.8863	-168.40	29.51	40.11	10.60	-2.3252180	-2.9096551	3999.50	11.9410000	19.60
198	0.8885	-169.95	29.51	40.59	11.08	-2.3211598	-2.9096870	3861.40	12.0050001	22.79
199	0.8901	-171.44	29.51	40.94	11.43	-2.4063771	-2.9097030	3669.50	12.0050001	26.18
200	0.8907	-172.87	29.51	41.18	11.67	-2.3495660	-2.9096069	3493.50	12.0050001	29.17
201	0.8913	-174.27	29.52	41.26	11.74	-2.3455079	-2.9096429	3365.60	12.0050001	30.86
202	0.8916	-175.59	29.52	41.27	11.75	-2.3495660	-2.9096949	3292.90	12.0050001	31.62
203	0.8918	-176.96	29.52	41.22	11.69	-2.2886958	-2.9096911	3256.50	12.0050001	31.55
204	0.8910	-178.27	29.52	41.05	11.53	-2.2318850	-2.9097350	3240.50	12.0050001	30.45
205	0.8901	-179.58	29.52	40.69	11.17	-2.2481160	-2.9096830	3239.10	12.0050001	27.86
206	0.8858	179.03	29.52	40.62	11.10	-2.3008699	-2.9096229	3230.30	12.0050001	27.44
207	0.8846	177.72	29.52	40.13	10.61	-2.3292758	-2.9096270	3230.30	12.0050001	24.24
208	0.8825	176.40	29.52	39.25	9.72	-2.2927539	-2.9096670	3234.70	12.0050001	19.33

209	0.8801	175.07	29.52	38.15	8.63	-2.1669569	-2.9096069	3243.40	12.0050001	14.48
210	0.8779	173.70	29.52	37.03	7.51	-2.2318850	-2.9097109	3253.60	12.0050001	10.64
211	0.8749	172.28	29.52	35.96	6.44	-2.2602901	-2.9096351	3263.80	12.0050001	7.78
212	0.8715	170.82	29.52	35.03	5.51	-2.2521741	-2.9096389	3273.90	12.0050001	5.82
213	0.8678	169.34	29.52	34.28	4.76	-2.2684062	-2.9096150	3285.60	12.0050001	4.52
214	0.8639	167.77	29.52	33.63	4.12	-2.2359421	-2.9095991	3295.80	12.0050001	3.57
215	0.8575	166.12	29.52	33.11	3.59	-2.1953630	-2.9096749	3305.90	12.0050001	2.90
216	0.8515	164.41	29.52	32.68	3.16	-2.2318850	-2.9095321	3316.10	12.0050001	2.41
217	0.8454	162.55	29.52	32.32	2.81	-2.2643480	-2.9096749	3327.70	12.0050001	2.03
218	0.8390	160.61	29.52	32.01	2.49	-2.2156529	-2.9095199	3339.40	12.0050001	1.73
219	0.8309	158.49	29.51	31.75	2.24	-2.2237680	-2.9095600	3352.50	12.0050001	1.50
220	0.8216	156.23	29.51	31.54	2.03	-2.2278271	-2.9094839	3364.10	12.0050001	1.32
221	0.8111	153.85	29.51	31.38	1.86	-2.1750729	-2.9095039	3375.70	12.0050001	1.18
222	0.7992	151.13	29.51	31.23	1.72	-2.2643480	-2.9095120	3388.80	12.0050001	1.07
223	0.7834	148.17	29.51	31.16	1.65	-2.2359421	-2.9094961	3403.40	12.0050001	1.01
224	0.7658	144.89	29.51	31.11	1.60	-2.2318850	-2.9095559	3419.40	12.0050001	0.97
225	0.7442	141.27	29.51	31.10	1.59	-2.2156529	-2.9094999	3435.40	12.0050001	0.96
226	0.7190	137.04	29.51	31.07	1.56	-2.2075360	-2.9094961	3449.90	12.0050001	0.93
227	0.6874	132.19	29.51	31.08	1.57	-2.1710148	-2.9095480	3465.90	12.0050001	0.93
228	0.6487	126.56	29.51	31.11	1.60	-2.2562320	-2.9095321	3480.40	12.0050001	0.95
229	0.6014	120.05	29.51	31.16	1.65	-2.2115951	-2.9094999	3495.00	12.0050001	0.98
230	0.5433	112.01	29.51	31.22	1.71	-2.1223190	-2.9095750	3511.00	12.0050001	1.02
231	0.5154	99.60	29.51	31.02	1.51	-2.2440581	-2.9095359	3528.40	12.0050001	0.88
232	0.3919	89.19	29.51	31.40	1.89	-2.1913049	-2.9095521	3547.30	12.0050001	1.14
233	0.3044	71.10	29.51	31.53	2.02	-2.1872470	-2.9095521	3566.20	12.0050001	1.23
234	0.2232	42.65	29.51	31.69	2.18	-2.1588409	-2.9095120	3588.00	12.0050001	1.35
235	0.1874	-2.16	29.51	31.90	2.39	-2.1791310	-2.9095399	3611.30	12.0050001	1.51
236	0.2407	-43.71	29.51	32.08	2.58	-2.2521741	-2.9095750	3636.00	12.0050001	1.66
!237	0.3403	-69.40	29.51	32.33	2.82	-2.2075360	-2.9095240	3653.50	12.0050001	1.86
238	0.4249	-88.34	29.51	32.67	3.16	-2.1507251	-2.9094441	3689.80	12.0050001	2.16
239	0.5011	-102.02	29.51	33.11	3.61	-2.1831889	-2.9095840	3724.70	12.0050001	2.58
240	0.5809	-111.62	29.50	33.51	4.00	-2.1466670	-2.9094839	3766.90	12.0050001	2.99
241	0.6133	-115.67	29.50	33.71	4.21	-2.1020291	-2.9095910	3791.60	12.0050001	3.21
242	0.7106	-117.36	29.50	32.53	3.02	-2.1710148	-2.9095440	3842.50	12.0050001	1.95
243	0.7060	-116.57	29.50	32.49	2.98	-2.1791310	-2.9095440	3848.30	12.0050001	1.91
244	0.6593	-108.31	29.50	32.15	2.64	-2.1385510	-2.9095480	3813.40	12.0050001	1.63
245	0.6041	-97.89	29.51	31.78	2.27	-2.1710148	-2.9096229	3778.50	12.0050001	1.35
246	0.5397	-85.44	29.51	31.44	1.93	-2.1953630	-2.9095559	3746.50	12.0050001	1.11
247	0.4784	-68.65	29.51	31.13	1.62	-2.1344931	-2.9096310	3723.30	12.0050001	0.90
248	0.3984	-48.38	29.51	30.85	1.34	-2.1669569	-2.9095950	3675.30	12.0050001	0.73
249	0.3444	-21.14	29.51	30.61	1.10	-2.1466670	-2.9096949	3660.70	12.0050001	0.58
250	0.3275	10.39	29.51	30.40	0.90	-2.2278271	-2.9096589	3641.80	12.0050001	0.47
251	0.3607	39.99	29.51	30.21	0.71	-2.1872470	-2.9096630	3624.40	12.0050001	0.36
252	0.4233	62.97	29.51	30.02	0.51	-2.1628988	-2.9096389	3606.90	12.0050001	0.26
253	0.4897	80.30	29.51	29.87	0.37	-2.2602901	-2.9096270	3589.50	12.0050001	0.18
254	0.5582	93.64	29.51	29.72	0.20	-2.2440581	-2.9096830	3572.00	12.0050001	0.10
255	0.6128	104.48	29.51	29.62	0.11	-2.2400000	-2.9096150	3557.50	12.0050001	0.05
256	0.6601	113.24	29.51	29.52	0.01	-2.2034791	-2.9096150	3544.40	12.0050001	0.01
257	0.6998	120.29	29.48	32.79	3.31	1.2823189	-2.9123960	2065.60	11.6450005	4.22
258	0.7313	126.43	29.47	32.71	3.24	1.5663770	-2.9125950	1946.40	11.5640001	4.36
259	0.7577	131.55	29.46	32.44	2.97	2.7350731	-2.9127181	1851.80	11.5059996	4.08
260	0.7799	136.10	29.46	31.99	2.53	2.1750729	-2.9125321	1737.00	11.4480000	3.51
261	0.7986	140.05	29.46	31.39	1.93	2.0736229	-2.9126229	1625.00	11.4239998	2.66
262	0.8137	143.48	29.46	30.64	1.18	2.3495660	-2.9128411	1536.30	11.3610001	1.58
263	0.8281	146.56	29.46	29.81	0.35	2.3576820	-2.9128289	1446.20	11.3199997	0.46
264	0.8385	149.35	29.46	29.12	-0.33	2.5240581	-2.9128730	1380.70	11.3199997	-0.42
265	0.8469	151.93	29.46	28.58	-0.88	2.4591310	-2.9128020	1326.90	11.3140001	-1.07
266	0.8556	154.22	29.46	28.14	-1.31	2.3820300	-2.9126790	1267.30	11.3490000	-1.60

267	0.8624	156.38	29.46	27.90	-1.56	2.3820300	-2.9125321	1233.90	11.4239998	-1.89
268	0.8679	158.37	29.46	27.80	-1.66	2.1750729	-2.9122770	1200.40	11.4770002	-2.04
269	0.8730	160.19	29.46	27.83	-1.63	1.2701449	-2.9121780	1169.90	11.5459995	-2.04
270	0.8778	161.95	29.46	28.00	-1.46	1.6799999	-2.9122140	1133.50	11.5749998	-1.92
271	0.8861	163.65	29.49	32.21	2.71	4.6423187	-2.9099290	1505.80	11.9809999	4.28
272	0.8897	165.17	29.49	32.33	2.85	4.4110150	-2.9096510	1406.90	11.9870005	4.87
273	0.8925	166.66	29.48	32.63	3.15	4.2284069	-2.9095869	1329.80	11.9870005	5.92
274	0.8950	168.07	29.48	33.07	3.59	3.9768121	-2.9095161	1273.10	11.9870005	7.46
275	0.8959	169.45	29.48	33.85	4.37	4.0579724	-2.9094679	1241.10	11.9870005	10.35
276	0.8963	170.67	29.47	34.70	5.22	4.3623199	-2.9095559	1219.30	11.9870005	14.10
277	0.8969	172.07	29.47	35.79	6.32	4.8533340	-2.9097190	1203.30	11.9870005	20.13
278	0.8975	173.30	29.47	36.83	7.36	4.5368123	-2.9095321	1197.50	11.9870005	27.37
279	0.8978	174.47	29.47	37.79	8.32	4.8371019	-2.9096069	1194.60	11.9870005	35.73
280	0.8980	175.71	29.47	38.55	9.08	4.9791322	-2.9094601	1188.80	11.9870005	44.05
281	0.8981	176.77	29.47	38.97	9.50	4.7315950	-2.9095869	1180.10	11.9870005	49.44
282	0.8982	178.01	29.47	39.18	9.71	5.0359430	-2.9095950	1174.20	11.9870005	52.48
283	0.8983	179.05	29.48	39.23	9.76	5.2023201	-2.9096589	1180.10	11.9870005	52.91
284	0.8981	-179.71	29.48	39.14	9.66	4.1959429	-2.9094760	1210.60	11.9870005	50.37
285	0.8981	-178.56	29.52	39.83	10.31	-2.2440581	-2.9095080	2804.30	12.0050001	25.92
286	0.8978	-177.40	29.52	39.75	10.23	-2.2684062	-2.9094520	2951.10	12.0050001	24.12
287	0.8975	-176.22	29.53	39.79	10.26	-2.2481160	-2.9095120	3032.60	12.0050001	23.70
288	0.8971	-175.15	29.53	39.88	10.36	-2.3008699	-2.9095480	3095.10	12.0050001	23.78
289	0.8972	-173.85	29.52	39.97	10.45	-2.3130438	-2.9094601	3157.60	12.0050001	23.83
290	0.8969	-172.60	29.50	36.77	7.26	-18.4718895	-2.9273510	1523.20	12.3990002	20.37
291	0.8965	-171.33	29.49	36.54	7.05	-22.2133408	-2.9309831	1610.50	12.4110003	18.05
292	0.8960	-170.00	29.49	36.29	6.81	-29.0104389	-2.9377770	1732.60	12.4160004	15.60
293	0.8951	-168.64	29.48	35.85	6.37	-39.2892799	-2.9462669	1844.60	12.4110003	12.85
294	0.8944	-167.23	29.47	35.05	5.58	-44.5646477	-2.9507170	1907.10	12.4049997	9.73
295	0.8936	-165.71	29.47	34.14	4.67	-47.0278397	-2.9530010	1942.00	12.4049997	7.05
296	0.8926	-164.09	29.47	33.31	3.84	-51.0898590	-2.9567959	1982.70	12.4340000	5.07
297	0.8915	-162.40	29.47	32.81	3.34	-51.6863785	-2.9566879	2049.60	12.4160004	4.00
298	0.8898	-160.61	29.47	32.41	2.94	-53.0458031	-2.9579561	2093.20	12.4110003	3.27
299	0.8878	-158.68	29.47	32.15	2.69	-55.8904495	-2.9600930	2123.80	12.4110003	2.86
300	0.8844	-156.53	29.47	32.19	2.72	-58.5605927	-2.9613130	2133.90	12.4049997	2.89
301	0.8782	-154.27	29.46	32.41	2.94	-62.2005920	-2.9647300	2090.30	12.4049997	3.28
302	0.8705	-151.77	29.46	32.31	2.85	-62.9919014	-2.9657271	2026.30	12.3929996	3.24
303	0.8606	-149.01	29.46	32.25	2.78	-64.8585663	-2.9664271	1974.00	12.3870001	3.22
304	0.8491	-145.97	29.46	32.32	2.86	-64.9234848	-2.9659810	1960.90	12.3350000	3.38
305	0.8357	-142.49	29.47	32.52	3.06	-65.0452271	-2.9652979	1984.20	12.3059998	3.67
306	0.8194	-138.66	29.47	32.79	3.32	-63.8400078	-2.9645989	2035.10	12.2659998	4.04
307	0.7989	-134.25	29.47	32.96	3.49	-63.3855171	-2.9633870	2101.90	12.2419996	4.21
308	0.7739	-129.10	29.45	32.59	3.14	0.6939131	-2.9127660	1783.50	11.9639997	4.39
309	0.7414	-123.16	29.45	32.98	3.53	0.5884058	-2.9128971	1841.70	11.8830004	5.05
310	0.7955	-120.54	29.46	33.95	4.49	11.5368099	-2.9111090	2648.70	11.9639997	5.05
311	0.8191	-126.27	29.46	33.81	4.35	10.9727507	-2.9109030	2622.50	11.9639997	4.85
312	0.8397	-131.28	29.46	33.36	3.90	10.0759401	-2.9106841	2555.60	11.9700003	4.20
313	0.8560	-135.54	29.46	32.71	3.25	9.2237701	-2.9105370	2430.60	11.9759998	3.37
314	0.8658	-139.51	29.46	32.29	2.83	8.9518852	-2.9103899	2323.00	11.9759998	2.92
315	0.8701	-142.85	29.46	32.26	2.80	9.0086985	-2.9103861	2250.30	11.9759998	2.96
316	0.8744	-145.93	29.45	32.25	2.80	9.6173925	-2.9106009	2020.50	11.9700003	3.29
317	0.8779	-148.73	29.44	32.27	2.84	10.3031902	-2.9105971	1678.80	11.9700003	4.02
318	0.8808	-151.22	29.43	32.31	2.88	10.1246395	-2.9104731	1475.20	11.9759998	4.67
319	0.8831	-153.48	29.43	32.31	2.88	9.5240583	-2.9103539	1350.20	11.9759998	5.09
320	0.8852	-155.58	29.43	32.11	2.68	9.3373928	-2.9101880	1296.40	11.9759998	4.82
321	0.8869	-157.53	29.43	31.90	2.47	9.0046406	-2.9102390	1284.70	11.9759998	4.36
322	0.8883	-159.32	29.43	31.76	2.33	8.9640589	-2.9100680	1299.30	11.9759998	3.99
323	0.8902	-161.03	29.43	31.77	2.34	8.3553638	-2.9099770	1364.70	11.9759998	3.82
324	0.8917	-162.58	29.43	32.19	2.76	7.9414511	-2.9099650	1505.80	11.9759998	4.32

325	0.8926	-164.09	29.44	33.15	3.71	7.0568132	-2.9098301	1758.80	11.9809999	5.62
326	0.8935	-165.46	29.45	34.58	5.13	5.7947841	-2.9095521	2088.90	11.9870005	7.94
327	0.8941	-166.81	29.47	36.44	6.97	2.9055080	-2.9089639	2584.70	11.9870005	11.36
328	0.8949	-168.10	29.49	37.65	8.16	0.9698552	-2.9086380	2850.80	11.9930000	14.43
329	0.8955	-169.30	29.51	38.57	9.05	-0.0284058	-2.9086339	2951.10	11.9989996	17.77
330	0.8963	-170.48	29.53	38.96	9.43	-1.0307250	-2.9086890	2984.60	11.9989996	19.47
331	0.8966	-171.61	29.53	38.83	9.29	-2.2034791	-2.9089200	3083.50	12.0050001	18.19
332	0.8969	-172.71	29.51	35.58	6.07	-12.9814501	-2.9216580	1350.20	12.2539997	16.42
333	0.8972	-173.81	29.51	35.39	5.87	-12.1049299	-2.9205289	1261.50	12.2480001	16.54
334	0.8971	-174.84	29.53	38.00	8.47	-2.2602901	-2.9094720	2885.70	12.0050001	15.62
335	0.8975	-175.91	29.53	37.87	8.34	-2.2886958	-2.9094760	2970.00	12.0050001	14.66
336	0.8974	-176.85	29.53	37.77	8.24	-2.3049278	-2.9094801	3010.80	12.0050001	14.07
337	0.8980	-177.97	29.53	37.79	8.27	-2.3008699	-2.9093690	3039.80	12.0050001	14.02
338	0.8981	-178.86	29.53	37.80	8.27	-2.3617399	-2.9094291	3064.60	12.0050001	13.94
339	0.8981	-179.86	29.52	37.92	8.39	-2.2684062	-2.9093730	3087.80	12.0050001	14.27
340	0.8983	179.09	29.52	38.05	8.53	-2.2765222	-2.9094090	3109.60	12.0050001	14.69
341	0.8983	178.21	29.52	38.07	8.55	-2.2034791	-2.9093771	3130.00	12.0050001	14.68
342	0.8980	177.24	29.52	37.91	8.39	-2.2927539	-2.9093969	3150.40	12.0050001	13.99
343	0.8980	176.10	29.52	37.43	7.91	-2.2156529	-2.9094560	3141.60	12.0050001	12.29
344	0.8979	175.23	29.52	36.86	7.33	-2.2521741	-2.9094441	3118.40	12.0100002	10.55
345	0.8977	174.15	29.52	36.09	6.57	-2.2886958	-2.9094369	3095.10	12.0100002	8.53
346	0.8974	173.10	29.52	35.31	5.79	-2.3536239	-2.9094720	3074.70	12.0100002	6.77
347	0.8970	172.16	29.52	34.63	5.12	-2.3008699	-2.9094999	3061.70	12.0159998	5.47
348	0.8964	171.00	29.52	33.87	4.36	-2.4307249	-2.9095681	3055.80	12.0159998	4.21
349	0.8961	169.91	29.52	33.23	3.72	-2.3982620	-2.9095750	3063.10	12.0220003	3.29
350	0.8955	168.90	29.52	32.61	3.10	-2.4956529	-2.9097190	3082.00	12.0220003	2.51
351	0.8949	167.63	29.51	31.57	2.05	-2.4307249	-2.9096711	3122.70	12.0220003	1.44
352	0.8942	166.48	29.52	29.83	0.32	-2.2562320	-2.9094839	3276.90	12.0050001	0.17
353	0.8937	165.12	29.52	29.19	-0.33	-2.2156529	-2.9094601	3300.10	12.0050001	-0.16
354	0.8926	163.87	29.51	28.66	-0.85	-2.2805800	-2.9094250	3316.10	12.0050001	-0.40
355	0.8916	162.39	29.52	28.15	-1.36	-2.2237680	-2.9094679	3330.70	12.0050001	-0.60
356	0.8908	161.08	29.51	27.91	-1.60	-2.2115951	-2.9093330	3111.10	12.0050001	-0.74
357	0.8894	159.46	29.51	28.01	-1.51	-2.2237680	-2.9092059	2914.80	12.0050001	-0.75
358	0.8884	157.89	29.51	28.12	-1.39	-2.1547830	-2.9090590	2829.00	12.0050001	-0.72
359	0.8869	156.14	29.51	28.20	-1.31	-2.1344931	-2.9088800	2802.80	12.0050001	-0.69
360	0.8852	154.09	29.51	28.46	-1.06	-1.5014490	-2.9087291	2674.90	11.9989996	-0.60
361	0.8833	152.12	29.51	28.77	-0.74	-0.5843478	-2.9086020	2487.30	11.9989996	-0.47
362	0.8813	149.88	29.51	28.80	-0.71	-0.1988406	-2.9086421	2465.50	11.9930000	-0.45
363	0.8778	147.53	29.51	28.86	-0.65	0.2069566	-2.9086139	2456.70	11.9930000	-0.42
364	0.8712	144.97	29.51	29.11	-0.40	0.6857972	-2.9087970	2449.50	11.9930000	-0.27
365	0.8633	142.13	29.51	29.30	-0.20	1.1808699	-2.9089200	2442.20	11.9870005	-0.14
366	0.8477	139.03	29.50	29.74	0.24	2.0086961	-2.9088960	2449.50	11.9870005	0.17
367	0.8362	135.59	29.50	29.95	0.45	2.3739130	-2.9089439	2448.00	11.9870005	0.33
368	0.8242	131.63	29.50	30.09	0.58	2.4713049	-2.9090950	2448.00	11.9870005	0.44
369	0.8067	127.05	29.50	30.28	0.78	2.5484059	-2.9091699	2448.00	11.9870005	0.60
370	0.7874	121.87	29.50	30.43	0.93	2.5930440	-2.9092579	2442.20	11.9870005	0.73
371	0.7625	115.74	29.50	30.54	1.04	2.5889859	-2.9091580	2400.00	11.9870005	0.84
372	0.7354	108.79	29.50	29.84	0.35	2.2765222	-2.9094961	2181.90	11.9870005	0.28
373	0.7113	100.17	29.49	30.30	0.81	1.0915940	-2.9090910	2231.40	11.9930000	0.68
374	0.6634	90.46	29.49	31.42	1.92	0.4666667	-2.9088960	2525.10	11.9989996	1.64
375	0.6518	77.51	29.50	31.59	2.09	0.0892754	-2.9087651	2682.10	11.9989996	1.71
376	0.5674	63.03	29.50	31.85	2.35	0.0243478	-2.9088011	2689.40	11.9989996	1.98
377	0.5301	44.97	29.50	31.83	2.34	0.0202899	-2.9087570	2661.80	11.9989996	1.99
378	0.4920	24.41	29.50	31.93	2.43	0.2272464	-2.9088440	2590.50	11.9989996	2.15
379	0.4705	-0.29	29.49	31.93	2.43	0.4828986	-2.9088089	2494.60	11.9989996	2.23
380	0.4928	-23.74	29.49	31.85	2.36	0.7020291	-2.9088211	2410.20	11.9989996	2.22
381	0.5413	-45.07	29.49	31.70	2.22	0.9820293	-2.9088640	2333.10	11.9930000	2.11
382	0.5765	-63.98	29.48	31.55	2.07	1.6272470	-2.9089839	2211.00	11.9930000	2.04

383	0.6216	-78.74	29.47	32.47	3.01	4.6829000	-2.9095910	1956.50	11.9870005	3.76
384	0.6726	-91.34	29.47	32.33	2.86	5.3443480	-2.9096470	1892.60	11.9809999	3.64
385	0.7133	-101.83	29.46	32.09	2.63	6.1194210	-2.9097071	1803.90	11.9759998	3.40
386	0.7502	-110.62	29.45	31.55	2.09	8.7530451	-2.9101441	1531.90	11.9639997	2.97
387	0.7735	-117.84	29.45	31.40	1.95	9.7594223	-2.9103620	1420.00	11.9639997	2.93